Doctoral Thesis

A Novel Approach for Monitoring Small-Scale Fisheries with GPS, GIS, and Remote Sensing Techniques

(GPS，GIS，リモートセンシングを用いた小規模漁業モニタリングの新しいアプローチ)

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2015

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CHAPTER 1

General Introduction

1.1. Small-scale fisheries

1.1.1. Definition and significance

The FAO (2012a) defines small-scale and artisanal fishing as: ‘fishing households [as opposed to industrial companies], using relatively small amount of capital and energy, relatively small fishing vessels [if any], making short fishing trips, close to shore’. The most common attributes are therefore households with limited range of operation, high dependency on local resources and low levels of technology and capital investment (Kolding, 2014).

There are some 51 million fishers in the world, and 98% of them work in small-scale fisheries. About 95% of the world’s fishers are in developing countries, producing 58% of the 98 million metric tons of the annual marine fish catch (FAO, 2007; OECD, 2008). The small-scale fisheries sector produces the bulk of the food fish catch for direct human consumption, income and livelihoods. Yet small-scale fisheries have been marginalized throughout the world through government policies that tend to favour large-scale, commodity-oriented fisheries (Berkes *et al.*, 2001).

1.1.2. Common issues

In small-scale fisheries, fishermen and coastal inhabitants are highly dependent on coastal fisheries for making livelihood. Management of small-scale fisheries is not an easy task because they involve many complexities and difficulties. Management of small-scale fisheries, as opposed to commercial fisheries, is challenged by many difficult issues; some are external problems such as economic and environmental ones and others are inherent problems such as folklore and traditions; some are related to the fisheries themselves and others are related to the fishers, fisheries scientists and fisheries managers. Table 1.1 describes the common issues to small-scale fisheries.

Except of these issues, the following problems are common to small-scale fisheries in the world, especially in developing countries. Monitoring is mostly lacking, fishermen's compliance is weak and regulations are not strictly enforced. With uncontrolled growth of fishing effort, fishing capacity is increasing. Eventually, many fish stocks have become depleted and many others have become overexploited (Hauge *et al.*, 2009).

Many approaches have emerged recently to deal with these issues to improve the fisheries management, especially in developing countries. Among these approaches are a precautionary approach, an ecosystem approach, a co-management approach and a right-based approach (Kurien and Willmann, 2009). The precautionary approach is recommended to manage fisheries under high uncertainty such as in data poor fisheries, and here management is pursued using the best available information. The ecosystem approach recommends managing the fisheries resources as components of whole ecosystem instead of single species independent of the ecosystem. Within the co-management approach, the responsibility of resource management is shared between a government and user groups. While the right-based approach defines both a right of fishers to use fisheries resources and allocation of fisheries resources to fishers who have the right to fish. Moreover, an integrated approach is also possible in which two or more approaches are brought together.

As an example of small-scale fisheries, fisheries management of Yemen is described in the second chapter and the common problems of small-scale fisheries are highlighted.

1.2. Existing approaches for fisheries monitoring

Fisheries monitoring aims to control the behaviour of resource users such as fishers to deter them from violating the rules (Berkes, 2001). Monitoring of large-scale fisheries is well developed in almost the entire world including those located in developing countries because it is feasible and reasonable enough to conduct and continue monitoring of a smaller number of larger vessels producing big catch quantities of high value species. Monitoring of these fisheries includes a variety of approaches, such as logbooks, electronic logbooks, on-board observers, on-board inspectors, vessel monitoring system (VMS), etc. VMSs are employed in commercial fisheries to allow environmental and fisheries regulatory organizations to monitor position, time at a position, and course and speed of fishing vessels. They are a key part of monitoring, control and surveillance (MCS) programs at national and international levels (Panjarat, 2008). The VMSs are continuously developed in technology and increasingly being used in monitoring of large vessels. An increasing number of states are adopting the VMSs and constantly revising their laws to make it obligatory on smaller vessels. Economic and practical feasibility coupled with strong enforcement of regulations have facilitated the use of VMS approach in large-scale fisheries. However, application of this approach to small-scale fisheries is hindered by non-feasibility, low compliance among fishers and low enforcement of the regulations. Monitoring of small-scale fisheries is limited to on-land monitoring through appropriate recording of landings and detection of illegal fishing practices. This may include fish sizes, fisheries during the fishing ban, illegal fishing gears, etc. At-sea monitoring is less employed in small-scale fisheries and VMSs are not applicable to small-scale fishing boats because of its big sizes and necessity of power supply to VMS on the boat. Moreover, VMS cost is a significant obstacle to its use in developing countries because of high costs of the system and annual subscription fee.

1.3. Minimization of data collection costs

Most of the budget for scientific research in fisheries sciences, which require field data collection, is allocated to data collection costs because they need to use research vessels with high costs for collecting fishery-independent data. The high costs of data collection restrict the quantity of data to be collected. In developed countries, financial allocation for research is well-channelled. However, researches in most developing countries are underfunded and this is reflected in the scarcity of research, inferior quality of publications and limited scientific contribution in these countries. Therefore, it is necessary for the developing countries, as well as for the developed countries, to search for cost-effective approaches to data collection.

Fishery-dependent data have been used frequently alone or altogether with fishery-independent data. These data have inferior quality but significantly cheaper when compared with fishery-independent data. However, its quantity is significant and represent the whole population in comparison with a small sample from the population represented in the fishery-independent surveys. Therefore, fishery-dependent data have been used despite its inherent errors and biases in favour of its quantity, availability and low collection costs. Scientists need to use these data with caution and develop methods to increase its usability and remove the inherent errors and biases.

In response to the limited research fund and low feasibility, developed countries started investigating approaches for data collection from the commercial fisheries (Dörner, *et al.,* 2014). One example, the National Marine Fisheries Service (NMFS), USA, started fairly recently developing electronic monitoring/electronic reporting system EM/ER to be used for data collection from the commercial fisheries (Loefflad *et al.,* 2014).

1.4. Cooperative research

Cooperative research between fishers and scientists aims to improve the knowledge base of fisheries management by integrating fishers and their knowledge into the science policy process, which is expected to generate broader acceptance of scientific-based management (Johnson and Densen, 2007; Johnson, 2009). This is one way in which scientific research can benefit from the commercial fishermen for data collection. The degree of willingness of fishermen to cooperate with scientists in data collection determines the quality and quantity of the data that can be collected.

While advocations for involvement of fishermen are arising, international fisheries management organizations stress the importance of involvement of fishermen in policy making process and propose to integrate their opinions in decision making to give any resulting resolutions legitimacy and acceptance among the fishing community. Fisheries scientists focus on fishers' knowledge and integrate it to improve stock assessment of fisheries. However, little has been done on cooperative research. Fishermen can provide fishery-dependent data and their fishing boats can be used as research platforms. It is important to search for appropriate framework in which fishermen and scientists can cooperate continuously in different stages of fisheries management process, ranging from planning for data collection to final production and adoption of management advice. Sustaining cooperative data collection is so important for minimizing research costs, especially in developing countries where research fund is scarce or lacking.

1.5. Catch per unit effort (CPUE) index

CPUE is often a main piece of information used in fisheries stock assessments and is usually assumed to be proportional to abundance (Hinton and Maunder, 2004). Collection of unbiased fishery-dependent information, such as CPUE, is often cost-prohibitive (Rudershausen, 2010). However, CPUE from commercial fisheries has been used to derive indices of relative abundance (Gulland, 1956; Large, 1992; Stefansson, 1996; Griffin *et al.*, 1997; Goni *et al*., 1999).

Assessment and management of fished cephalopod populations is a relatively undeveloped field. Most of stock assessment methods applicable to finfish fisheries have been tried out on cephalopods, but no standard approach has resulted. Perhaps the most obvious difficulty in treating cephalopods in the same way as finfish for the purposes of assessment is their universally short lifespan and generally single year-class, which is totally dependent on recruitment success in the fishing year population (Boyle and Rodhouse, 2005). Stock-recruitment relationships, recruitment indices, swept-area biomass estimates, production models, cohort analysis, yield-per-recruit models, length-based cohort analysis and depletion estimates of stock size have all contributed to cephalopods stock assessment (Pierce and Guerra, 1994).

The depletion method derived from Leslie and Davis (1939) and De Lury (1947) is the stock assessment methodology commonly used to assess cephalopod stocks, and it is considered as the least expensive methodology (Rodhouse *et al.,* 2014). Depletion of the stock during the fishing season is usually monitored from changes in CPUE throughout the season (Boyle and Rodhouse, 2005). In theory, this model estimates the consequences of the removal of individuals (natural or fishing mortality) on a population and determines the size of the population at the beginning of each fishing season (Hilborn and Walters, 1992). These methodologies are suitable to perform a real-time modelling of the data collected in a short period (in particular when exploitation does not exceed 1 year; Boyle and Rodhouse, 2005). Estimation by this method enables the introduction of management measures aimed at allowing a fixed proportion (40%), or an absolute quantity, of the pre-season stock to escape from fishing and contribute to the following recruitment. This target can be achieved by adjusting the fishing effort, for example, by early closure of the fishing season. Despite the obvious difficulties caused by immigration to, and emigration of a stock of target species from the fished stock, the Leslie–De Lury method is currently the most widely used assessment approach for management of cephalopods (Boyle and Rodhouse, 2005).

1.6. Objectives

This study aims to develop a monitoring scheme for the small-scale fisheries of Yemen through two case studies, the pelagic Indian mackerel fishery and the demersal pharaoh cuttlefish fishery. GPS, GIS and remote sensing techniques are integrated and tested to collect data on the resource use and spatio-temporal distribution of both effort and catch per unit effort at fine scale. It also aims to test the use of fishing boats as scientific platforms in the collection of data for scientific research and aims to establish a long-term connection with the resource users. The use of satellite remote sensing data is aimed to investigate its potential in analyzing the environmental variables responsible for fishing ground formations of small-scale fisheries.

1.7. Thesis structure

The thesis consists of six chapters: chapter 1 general introduction, chapter 2 characterization of fisheries management in Yemen, chapter 3 materials and methods, chapter 4 small-scale Indian mackerel fisheries, chapter 5 Pharaoh cuttlefish fisheries, and chapter 6 general discussion. Chapter 1 describes the background of the study to explain the necessity of monitoring of small-scale fisheries with participation of fishers. Chapter 2 introduces the present status of Yemeni fisheries and their management. Chapter 3 explains the materials and methods to obtain data of fishing grounds and landings, satellite remote sensing data as environmental parameters in fishing grounds and analysis method using ArcGIS. Chapters 4 and 5 are dedicated to monitoring results of Indian mackerel fisheries and Pharaoh cuttlefish fisheries in Yemeni Red Sea, respectively. Chapter 6 discusses implications of the approach developed in this study for small-scale fisheries management.

Table 1.1. The common issues to small-scale fisheries.

	ISSUES
Fisheries	multi-species; multi-gears; highly dispersed fishing grounds; shift of target species and fishing gears; widespread illegal, unreported and unregulated (IUU) fishing
Fishers	low awareness; lack of self-organization; weak role of cooperatives in fisheries management
Fisheries officials	lack of political will and capacity to manage the fisheries resources
Fisheries strategies	advocating harvesting; less attention to conservation (with slow move to conservation upon realizing the depletion of their fisheries resources)
Legislations	legislations are underdeveloped and less regularly updated to deal with emergent conservation goals
Fisheries scientists	fisheries scientists are underqualified and less equipped with the suitable tools to deal with the complexities involved in small-scale fisheries
Research fund	limitation of funds for scientific research
Data requirements	lacking due to the unreliable catch statistics
Fisheries management financing	limited financial allocations for different stages of fisheries management including the funds allocated for monitoring, control and surveillance activities

CHAPTER 2

Characterization of fisheries management in Yemen

2.1. Introduction

While most of the world fish production originates in small-scale fisheries of developing countries (FAO, 2014), fisheries management in these countries adopts the same methods of fisheries management used for commercial fishes caught by large-scale fisheries in the developed countries (Ruddle and Hickey, 2008). Policy makers in developing countries do not search for alternative approaches and think that the formal stock assessments methods used for commercial fishes in developed countries are the only way to manage the fishery resources in their countries (Mahon, 1997). This has resulted in most of these fisheries unmanaged (Svendrup-Jensen, 1999). Policy makers, scientists and fishery managers should realize the differences in scale and nature between the small-scale fisheries and large-scale fisheries. They need to understand the context in which small-scale fisheries operate and try to develop management systems suitable to the context of these fisheries.

Fisheries management in Yemen until 1999 was the responsibility of the fisheries department of the Ministry of Agriculture before the establishment of the Ministry of Fish Wealth (MFW). The authorities' policy has been development-oriented, in which high emphasis is placed on the economic benefits gained from the fishery. Throughout the past 20 years, the fisheries policy has encouraged investments in the fisheries sector, increases in fish production, and the development of the fishing industry (Bonfiglioli and

Hariri, 2004). While the policy encourages sustainable use of fisheries resources, neither detailed fishery management plans (FMPs) nor operational objectives exist to address policy objectives. Moreover, planning and policymaking is practiced without proper knowledge of the resources (Wagenaar, D'Haese, 2007). During the last few years, the national authority started to transfer management responsibilities from the central level to the local level, and has already established local fisheries authorities to be responsible for fisheries management at the local level. This restructuring is part of decentralization process aimed to improve management of the sector. However, transfer of responsibilities is said to be slow (Setlur, 2013).

The aim of this chapter is to analyze the overall management of the fisheries sector, and to critically review the existing legislative, policy and regulatory frameworks, the compliance and enforcement mechanisms, and the impacts that these arrangements have on the nature and extent of illegal, unreported, and unregulated (IUU) fishing. The chapter proceeds, at first, by describing the fisheries management from a developing country perspective, with emphasis given to the inherent problems and recommendations on approaches to fisheries management, which fit their context. Second, it gives a description of the context in which fisheries in Yemen are operated, details the contributions of the fisheries to the society and to the economy, and the problems arising from both outside and inside the sector. It also presents the historical development of the fisheries, distinguishes the two small and large-scale subsectors, and describes the key fish species of the fisheries. Then it describes the fisheries management in Yemen, with emphasis given to the policy and regulatory frameworks and how appropriate these tools are. This is followed by a description of the compliance and enforcement tools in both the small and industrial subsectors. Finally, the chapter presents the current status of IUU fishing, its different types, situations where it occurs and the drivers and incentives behind its occurrence.

2.2. Fisheries management in a developing country context

In the typical context of fisheries in developing countries, management has been challenging due to the complex nature of the inherent social-ecological systems (Mahon et al., 2008; Garcia, 2003). These are frequently described as labor intensive, multi-species and multi-gear fisheries sparsely distributed along the coast and associated with high levels of community dependence (Panayotou, 1982; Charles, 1991; Charles, 2001). In such a context, it is difficult to control fishermen’s behavior or to enforce regulations (Raakjær, 2003).

In the northwest Indian Ocean, fisheries management is characterized by the following four factors (Morgan, 2006): (a) the almost total absence of comprehensive stock assessments upon which management decisions must be based, combined with a generally poor statistical database on landings (and their composition) and fishing efforts; (b) the regional and shared nature of many of the fish stocks which are asymmetric to the poorly developed institutions for regional management; (c) the development strategy of national fisheries legislation and policy in most countries despite the apparent over- or fully exploited status of many fish stocks; and (d) a general lack of success at the regional and national levels in measuring and controlling fishing capacity, particularly in the small and important artisanal sector.

In the developing countries, poor management arises in part from the governance or policy-making authorities, in which the lack of the political capacity or will affects the quality of the fisheries management (Carbonetti et al., 2014). In these cases, stakeholders are rarely considered in planning or in decision-making, which results in low compliance with the regulations. Besides, limited monitoring and/or enforcement of the regulations, creates incentives, which favor non-compliance (Hatcher and Pascoe, 2006). Moreover, the management authorities in most developing countries lack the capacity to prepare fishery management plans and this is due to the lack of the necessary expertise and essential fund for research, monitoring and enforcement.

The approach of fishery managers to conservation and management in developing countries frequently appears to be driven by the perceived need for stock assessment, rather than by the need to implement the most effective management regime possible, based on what is feasible and affordable, given the nature of the fishery and the human resources available (Mahon, 1997; Mackinson, 2011). This mismatch partially arises from the fact that the fishery managers and scientists were educated in the west or received training on management approaches used in the developed countries (Ruddle and Hickey, 2008; Mahon, 1997), which requires intensive researches and substantial fund beyond the capacity of most developing countries. Finally, these approaches do not necessarily fit the context of fisheries of the developing countries. The provisions of the Code of Conduct for Responsible Fisheries as they relate to the uncertainties and the lack of data in the developing countries, recommend adopting the precautionary approach to fisheries management (FAO, 1995). Management tools within this suggested approach do not require much data to formulate, are easy to monitor fisheries resources and activities and easy to enforce with limited expertise and funding requirements. The code also stresses the importance of research and capacity building for those countries.

Scientists from the developed countries increasingly recognize the failure of fisheries management (Andrew, 2007; Tim, 1998; Daw, 2005). They further express their concern that the science they have produced may not serve the needs of researches on small stocks in many developing countries (Ruddle and Hickey, 2008; Mahon, 1997). In searching for innovative approaches, they called upon a multi-disciplinary approach which takes into account the social, economic and ecological systems in which these fisheries occur (Hughes, et al., 2005; Caddy, 1999; Berkes, 2003; Kates et al., 2001; Hauck, 2008). In this stream, community-based management or participatory management has grown out of developing country needs, and has involved stakeholders as partners in fisheries management (Mahon, 1997; Mackinson et al., 2011; McCay and Jentoft, 1996). Taking into account the fast population growth in these countries, it is necessary to realize that the resources at some point in time will fall short and will not be capable of delivering the same benefits to this growing population. Therefore, it is necessary to adopt sustainable management approaches and this inevitably requires to gradually reduce dependence on the resources. Thus, developing countries should search for suitable cost-effective management approaches besides the above-mentioned.

2.3. Fisheries status and historical development

Yemen is located in the southwest corner of the Arabian Peninsula and is bounded by 2,520km of coastline that extends along the Red Sea, the Gulf of Aden, and the Arabian Sea. The fisheries sector is considered particularly important because it provides various social and economic benefits to the coastal communities and to the wider community. At both national and local levels, fisheries contribute to food security, employment, domestic income, foreign exchange earnings, and fiscal revenues. The fishing industry is dominated by the small-scale sector, which currently supports the livelihoods of an estimated 83,157 small-scale fishermen and 583,625 of their dependents, for a total of about 667,000 people (IFAD, 2010; MFW, 2012). In addition, an unknown but relatively a large number of people are also engaged in post-harvest processing, marketing, and value addition (Bonfiglioli and Hariri, 2004). The fisheries sector contributed 1.9% of Yemen's $26.24 billion gross domestic product in 2009 (YFSP, 2010). Next to oil exports, fisheries constitute the second largest export earner and account for 1.5% of the national labor force, supporting the livelihoods of 3.2% of the national population (MFW, 2012). The fisheries industry, with its largely rural location, remains the largest if not the sole source of income for coastal communities (YFSP, 2010).

The major challenges hindering economic development in Yemen include political instability, a lack of security, and widening areas of conflicts (IMF, 2012). Within the fisheries sector, poor governance, the absence of appropriate legislation, and inadequate infrastructures have been major problems (Hariri, 2000) that undermine the social and economic contributions of the fisheries sector. Recently, frequent fuel and electricity shortages, paired with subsequent price increases, have increased hardship among fishermen (World Bank, 2012). Widespread piracy in the Gulf of Aden and the Arabian Sea has been a major concern and has restricted productivity of fishermen from these areas (IFAD, 2010; MFW, 2012). According to the Yemeni government figures released in July 2009, piracy in the Gulf of Aden has cost the country an estimated $200 million in lost fishing revenue and other revenue (Boucek, 2009).

Moreover, Yemen has the world's fourth fastest growing population (3.0% in 2013) (UNDP, 2013) and the corresponding increase in unemployment rates (17.8% in 2010; 29% in 2012) (WB, 2013) will pose more threats to the already overexploited fishery resources and will cause further damage to the important coastal habitats. A national assessment carried out by the United Nations Development Programme in 2010 to assess progress in Yemen toward achieving Millennium Development Goals found that Yemen is unlikely to achieve most of the Goals by 2015 due to chronic underdevelopment, security problems, and a lack of financial resources (WB, 2012).

Recently, a new national fisheries strategy (2012–2025) has been formulated and has identified fisheries as a potential sector to food security and to create more employment opportunities (MFW, 2012). The strategy has identified short-term, mid-term, and long-term objectives and a timeframe to achieve these objectives. This strategy and its announced objectives recognize the major uncertainty of the sector, in which production estimates are highly uncertain and the stock status of most species is unknown. However, the strategy did not prioritize objectives nor did it introduce practical solutions to the major obstacles encountered in the sector, particularly the poor governance and uncertainty of the overall performance of the sector. Moreover, the strategy did not account for the high vulnerability and low resilience inherent in fisheries resources in general.

Prior to unification in 1990, the two separate entities of Yemen pursued different fisheries development policies; while the state in the north adopted a policy of supporting artisanal sector development, the state in the south pursued a policy of supporting large-scale industrial fishing (Morgan, 2006). After unification, the authorities encouraged a policy of supporting the artisanal sector development and gradually eliminated the agreements with the industrial fleets. As a result, the number of fishermen and fishing boats has increased rapidly and production estimates reached a peak of 256,300 tons in 2004 before dropping to 130,591 tons in 2008 (MFW, 2012). The catch per unit of effort

(CPUE) has simultaneously decreased with time (MFW, 2012; Tesfamichael et al., 2014; Tesfamichael, 2012).

In the absence of proper governance, industrial fleets have caused not only fish stock depletion but also major destruction to fish habitats (Shaher, 2007; Gladstone et al., 1999). In line with the announced fisheries strategy that gives preference to the artisanal sector, new licences for industrial vessels have not been granted since 2004. Currently, there is no licensed industrial fishing in Yemen and there are only a few coastal fishing fleets with illegal licences (using licences of artisanal boats) in the Gulf of Aden and the Arabian Sea. Industrial fleets are registered to fish for almost all different kinds of fish, including pelagic fish. However, reporting of catches have never included any pelagic fish. Moreover, it is believed that these trawlers are poaching significant quantities of tuna and tuna-like species. Furthermore, significant quantities of fish are being captured illegally by unlicensed industrial fleets; these fish are being transferred directly to other countries (Hariri, 2000; Feidi, 1998).

Due to the limited employment opportunities available to the coastal inhabitants, increased domestic demand, and the open-access nature of fisheries, the number of fishermen has increased rapidly. Moreover, the return of one million expatriates from Saudi Arabia after the 1991 gulf crisis (Baldwin, 2005) has also added to the numbers of workers entering artisanal fishing (Shaher, 2007; Gladstone et al., 1999). Subsequently, fishermen numbers have increased three-fold between 1990 and 2010. Most of the recent growth has occurred in the Red Sea region where both fishermen and fishing boats numbers have increased four-fold between 2000 and 2010 (MFW, 2012). This rapid growth in the past decade is attributed, in part, to changes in national policy that have led to a reduction of the industrial fleet.

Fish exports have witnessed significant increases and reached 110,000 tons in 2010, which is nearly 58% of the total fish production (MFW, 2012). This increase is attributed to the sector's increased productivity and increased compliance with international standards of quality control applied to fish exports. Despite the recent decrease in total catch compared with 10 years ago, fish exports have increased constantly; this increase seems to occur at the expense of local consumption and has caused significant increases in fish prices in local markets (SMEPS and KIT, 2009).

Artisanal fishing accounts for well over 90% of the total production (IFAD, 2010). The key fisheries resources, shown in Table 2.1, include pelagic fishery for tuna and tuna-like species and demersal fishery for fish, cuttlefish, shrimp, and lobster. Tuna and tuna-like species and cuttlefish are prevalent in the Gulf of Aden and the Arabian Sea, whereas demersal fish are more abundant in the Red Sea.

Key pelagic species include yellowfin tuna, longtail tuna, little tuna, narrow-barred Spanish mackerel, Indian mackerel, anchovy, and sharks; key demersal fish species include emperors, groupers, snappers, and jacks (IFAD, 2010; Hariri et al., 2000). Despite the lack of comprehensive stock assessment studies and reliable catch statistics, it is believed that most fish stocks, except small pelagic species for which there is no market demand, are either fully exploited or overexploited (Morgan, 2006); interviews with fishermen and different stakeholders confirm these beliefs. Cuttlefish (*Sepia pharaonis*) has been harvested since 1967 by industrial fleets in the Gulf of Aden and the Arabian Sea region. The intensive trawling on their spawning aggregations has led to overfishing and a major decline of the fishery by 1982–1983 with reported annual landings falling from around 9,000 to 1,500 tons. Landings of the rock lobster (*Panulirus homarus*) virtually collapsed to near zero in the late 1990s from peaks of around 400 tons in the early part of the decade. This collapse was attributed to the widespread use of nets rather than traditional traps to capture lobsters (Morgan, 2006). Large-scale harvest of sea cucumbers started in 2003 with the advent of air compressors, which facilitated diving; this process led, a few years later, to the collapse of the fishery (PERSGA, 2009).

Many important demersal fish stocks and some pelagic species, such as Indian mackerel (Gladstone, 1999), narrow-barred Spanish mackerel, and sharks (Shaher, 2007; Pramod et al., 2008), have experienced severe overfishing. The lack of FMPs, widespread IUU fishing, uncontrolled growth of fishing effort, and weak compliance and enforcement arrangements have led to significant economic losses associated with the suboptimal use of the resources, which has in turn resulted from weak and ineffective governance and subsequent overfishing.

Small-scale fishermen typically use two types of fishing boats: small fiberglass boats called "*huris*" in Arabic, 7–16m long, with outboard engines and 2–6 crew members, and larger wooden boats called "*sambuks*" in Arabic, 10–20 m long, with inboard or outboard engines and with a crew from 10 up to 25 or more (Bonfiglioli and Hariri, 2004; IFAD, 2010). *Huris* were traditionally used for single day trips in inshore waters, within 40 kilometers of the shore (Bonfiglioli and Hariri, 2004). However, due to overfishing and decreasing CPUE, and increasing operation costs (particularly fuel prices), fishermen tend to spend longer (up to 10 days) at sea in an attempt to harvest more catch to get a better return on their investments. *Sambuks* are used for longer trips ranging from a few days to three weeks (Bonfiglioli and Hariri, 2004; IFAD, 2010).

Fishing is highly seasonal, with activity restricted by the monsoon winds (the northeast winter monsoon ranges from November to February and the southwest summer monsoon ranges from June to September) (Bonfiglioli and Hariri, 2004). As a result, fishermen tend to relocate their fishing activities (Wagenaar and D’Haese, 2007) or shift their fishing gear to target different species. Shifting of either fishing gear or target species is also frequent with seasonal changes in fish production; fishermen shift when the fishery is not profitable and return when it is profitable again. For example, fishermen targeting demersal fish along the Red Sea typically shift to cuttlefish following a decrease in demersal fish catches.

2.4. Assessment of the current status of fisheries management

Fisheries management usually must have a policy framework which sets objectives to achieve and mechanisms to follow in decision-making. Next, it must have a suite of laws and regulations to control stakeholders' behavior. Finally, it must have an enforcement power to ensure compliance and implementation of these rules in practice. How appropriate these tools are to a specific fishery, will determine the type and success of the resulted management.

2.4.1. Legal, policy, and regulatory framework

The stated objectives of the fisheries sector include protection of fish resources and the environment, the encouragement and regulation of investments in fishing and marketing, provision of post-harvest facilities, setting measures and norms to regulate fishing with a gradual replacement of industrial fishing by artisanal fishing, and the encouragement of aquaculture investments. Despite these stated objectives, the policy during the past three decades has been development-oriented and has centered on encouraging investment in fisheries exploitation and increasing fish production. To ensure sustainable resource conservation and management, the fishery should have an effective legal and administrative framework and an appropriate compliance and enforcement tools to ensure the subsequent implementation of the legislation.

The regulation of exploitation of fish resources is controlled by the law no. 2 of 2006, which, when issued, cancelled the law no. 42 of 1991 and the law no. 43 of 1997. This law prescribes the requirements of fishing boats with regards to fishing, specifies the powers of the minister and the competences of the MFW, the competences of the branches of the MFW in coastal cities (currently contained within the Fisheries Authorities), and specifies the requirements of coastal and industrial vessels and the penalties for violations of the provisions of this law.

Fishing vessels are classified according to boat length and engine power. An artisanal boat can have an overall length up to 21 m and outboard engine up to 150 hp; coastal boats can be up to 40 m long with outboard engines up to 1100 hp. Industrial boats can be up to 70 m long with outboard engines up to 3000 hp. To reduce conflicts among different categories of fishing vessels, the law has specified different areas for each vessel category. The first 5 miles from the coast is allocated to artisanal boats, beyond 5 miles for coastal boats and beyond 12 miles for industrial boats.

FMPs addressing different key species are lacking, which is due, in part, to limited knowledge about resources. This lack of knowledge results from the limited human and institutional capacity in terms of developing species-specific management plans. There are very few management measures with provisions provided for in the fisheries legislation. Closed seasons, where fishing is prohibited, are the most widely used management measures to protect and conserve the most important commercial species. Closed seasons are currently used to manage shrimp, rock lobster, and cuttlefish resources (Morgan, 2006).

Opening and closing of seasons are regularly announced by the MFW upon receiving the initial information and advice from the Marine Science and Biological Research Authority. The discarding of fish is prohibited in all fisheries. The collapse of the sea cucumber fishery led, in 2007, to a complete ban on the capture and trade of all sea cucumbers within the country (PERSGA, 2009).

Management measures related to the valuable rock lobster include minimum size of 19 cm, gear type is restricted to traps only, quantity of gear is restricted to 60 traps per boat, and a prohibition on the taking of egg-bearing lobsters. If egg-bearing lobsters are accidentally captured, they must be returned to the sea. Measures targeting pelagic species are lacking, except for a law prohibits the use of light when using purse seine nets.

While the power and ability to execute within the current legislation are given to the minister and the ministry, only minimal action has been taken. Managing the fisheries, issuing any urgent norms, or making any required reforms or amendments have been limited. For example, while the law gives the minister the right to issue the specifications pertaining to different fishing gear, fishing gear remains largely unregulated. No specifications have been made regarding net sizes, mesh sizes, the minimum sizes of different species allowed to catch, specific areas for different fishing gear, or sensitive areas where trawling is prohibited.

Even though the fisheries act (no. 2/2006) is relatively new, it does not seem to integrate many of the recent changes in international policy, including the 1982 United Nations Convention on the Law of the Sea (UNCLOS), FAO Compliance Agreement, UN Fish Stock Agreement, and the 1995 FAO Code of Conduct for Responsible Fisheries. By signing these treaties, countries have agreed to adopt the new policy and have shown their commitment to address sustainable conservation and exploitation of marine resources to maintain their productivity for future generations. In order to ensure Yemen's commitment, the fisheries act is supposed to make the necessary amendments in the fisheries governing laws to meet these emerging fisheries policies. It is necessary that the fisheries law be broadly based on the precautionary approach, particularly in the case of least developed countries such as Yemen where the status of most fish stocks is unknown and funds for research are lacking. During the last two decades, aquaculture development, though stressed in policy, did not make any progress and the lack of aquaculture legislative framework has been one of the major obstacles to aquaculture development. Therefore, it is necessary to investigate these obstacles and make the necessary legislative and regulatory reforms to address these issues.

2.4.2. Compliance and enforcement

Enforcement of regulations by the enforcement authorities is weak, which results in fishermen having a low compliance with regulations. Compliance and enforcement tools prescribed by the law include instruments for both artisanal and industrial fisheries. In the artisanal sector, monitoring is restricted to random dockside inspection and routine inspection at landing sites, and inspection is not strictly enforced. On-land enforcement tools consist of on-land observers and quality observers.

The tasks allocated to the on-land observers include reporting of illegal fishing gear, reporting of unlicensed fishing boats, illegal fishing during the closed seasons, capture of illegal species or sizes, unloading at unofficial landing sites, reporting of illegal means of transporting fish, and reporting of any violations to the laws and regulations of the fishery.

Compliance and enforcement tools within the industrial fisheries include the requirement of the coastal and industrial boats to take onboard 2–4 observers, the use of Vessel Monitoring System, the real-time reporting of catches at sea, and the unloading of fish should be at specified ports in Yemen.

Coastal and industrial boats are required to keep logbooks, in the format specified by the MFW, to record the catch in terms of species and quantity, the coordinates of each of the fishing locations, and the depths and times spent fishing. However, logbooks are not used with the artisanal boats, even though the law entitles the MFW to ask artisanal boats larger than 15 m long to keep logbooks to record the specifications of the catch.

Enforcement incentives provided for in the law are generally low and lack publicity. The law has specified a reward, 10% of the reported infringement, for any person detected and reported any violations to the laws and regulations of the fisheries. However, reporting of violations still occurs infrequently, in part due to the lack of publicity of these rewards and a lack of trust in competent authorities.

The penalties are sometimes not severe enough to ensure compliance with and enforcement of regulations. Moreover, the fines are not prescribed for different levels of violations and sometimes do not differentiate between the artisanal and industrial fishing activities. The law did not empower to the MFW to judge on violations instead of lengthy court cases.

In case of industrial fleets and companies, sanctions for violations include provisions for the revocation or suspension of the authorization to fish and are sometimes as severe as the confiscation of the boat and its equipment. However, on-board observers and inspectors rarely report the violations and are sometimes forced not to report. If violations are indeed communicated to authorities, penalties are rarely enforced. Similarly, reporting of violations and enforcement of regulations is largely lacking within the small-scale sector, which affects compliance levels among fishermen. In fact, the level of compliance of fishermen with laws and regulations has been negatively affected by the widespread corruption in the policymaking authorities, in the judicial systems, and in everyday local administrations.

2.4.3. Present status of IUU fishing

It is obvious that fish stocks have been depleted in many areas in the world's oceans and seas due to poaching, smuggling, overfishing, and violation of local, regional, and international laws (MRAG, 2005; Öztürk, 2013). IUU fishing is most detrimental and most likely occurs in countries where governance is weak and corruption is rampant, such as most developing countries (Sundström, 2012; Agnew, 2009). This widespread IUU fishing in many developing countries has several severe environmental, social, and economic consequences, including unfair competition, loss of biodiversity, loss of income, and even loss of human lives (Öztürk, 2013).

IUU fishing is a major issue and a source of serious concern for Yemeni fisheries. Such fishing undermines the contribution of fisheries to the food security, to income and livelihood and to the national economy. The widespread IUU fishing in Yemen is one of the major consequences of the weak governance reflected in the weak legislative, policy, and regulatory frameworks. There is no national plan to combat IUU fishing. Sanctions are not specified for different types of violations and, where stated, are not sufficient to act as deterrents with the level of violations. The drivers behind IUU fishing include the lack of political will to prevent, deter, and eliminate IUU fishing, low levels of fines, the absence of effective monitoring, control, and surveillance (MCS) activities, and the weak enforcement of the laws and the regulations.

IUU fishing in Yemen may occur in different forms. Illegal fishing practices within the small-scale sector include discarding of significant quantities of fish during bottom trawling and purse seining, the use of light when fishing using purse seines, the use of small-mesh nets, and the use of destructive fishing gear (particularly in sensitive habitats such as coral reef areas). In case of industrial fisheries, due to weak MCS systems, violations include operating in areas allocated for artisanal fishermen and causing destruction to their fishing gear, fishing during the closed season, transshipment at sea, under-reporting, discarding large quantities of fish, and unloading at ports unspecified by the managing authority. Moreover, significant poaching by unlicensed foreign trawlers and purse seiners has been reported.

Discarding of fish, despite it is banned, is widely practiced by both industrial and artisanal fisheries. It is associated with almost all activities of industrial fishing and with certain fishing gear in the artisanal sector. For example, the small-scale bottom trawl fishery for shrimp is usually associated with discards of large quantities of small and juvenile demersal fish several times larger than the target species (Pramod et al., 2008).

The MFW reports that fishermen and/or the fisheries cooperatives tend to misreport catches to avoid paying the levy (IFAD, 2010; Hariri, 2000; Pramod et al., 2008). In one case study, which highlights the level of misreporting, the Indian Ocean Tuna Commission (IOTC) estimated the catch for tuna and tuna-like species caught by artisanal boats in the year 2004 at around 42,000 tons, which is five times higher than the official reported figures (Herrera and Lepere, 2005). Under-reporting or non-reporting typically increases in remote areas where fish are sold directly to the traders or are sold in the sea to a receiving boat or sold at unofficial landing sites. Hence, the catch from these areas does not enter into the official statistics and production estimates from these areas are estimated only if transported to the main cities or from the export figures at export outlets. It is noteworthy that significant quantities of small or low-value fish are usually sold directly to traders originated from the countryside and that these quantities typically do not pass through the catch-collection system.

Landing sites along the Gulf of Aden are operated by the cooperatives that provide a wide range of services, including auctioning, marketing, facilities provision, maintenance, health care, and credit provision. However, cooperatives along the Red Sea are non-functional and provide far fewer services (Qasem, 2007). Landing sites and auction yards in remote areas do not have the necessary facilities such as ice plants, storage, and marketing services. Moreover, cooperatives in these areas typically are not active and fishermen membership rates are very low. These areas mostly lack basic infrastructure. As a result, fishermen refuse to pay the levies imposed by the authorities. These practices lead to significant losses on both sides; the fishermen side and the state side. Fishermen get paid less for their catch because the prices are under the control of the traders, who dictate the prices, and the state loses control over the data collection system and loses the levies. Furthermore, this process minimizes the funds available for fisheries management and belittles the economic potential of the fishery.

Due to the weak MCS systems, many foreign vessels used to fish illegally in the Yemeni waters and the catch from these vessels was typically transferred to the receiving country, where the catch was unloaded (Feidi, 1998). Until the process was stopped in 2004, industrial fishing was carried out according to the agreements signed with these fleets to fish in the Yemeni waters; however, many other foreign vessels are still frequently reported to illegally operate due to the low chances of being discovered and the weak enforcement of laws and regulations.

This practice of illegal transfer of the catch into or out of Yemen contributes significantly to the current uncertainty in catch statistics. Direct transfers from Yemen into other countries, mainly Egypt, were estimated in 1999 at up to 40,000 tons per annum (PERSGA, 2009; WB, 1999) and this quantity typically did not enter into the official catch statistics. Moreover, a large quantity of fish originating from Eritrea is illegally transferred and sold in the Yemeni market, where market circumstances are better than in Eritrea (Moussalli and Haile, 2001). However, no accurate estimates are available for this amount. This amount, regardless, will not significantly affect the total catch of Yemen because of the relatively small production estimate of Eritrea, which is currently between 4,000 and 12,000 tons per year (Tesfagiorgis, 2010).

Table 2.1. Key species in the artisanal fishery and their contribution in catch and value in 2012

Fish Group	*Species*	*Catch (tons)*	*% of total*	*Value (USD, in millions)*	*% of total*	*Group total (tons)*	*% of total*
	Yellowfin tuna	35669	15.6	149.7	27.828		
	Longtail tuna	4823	2.1	18.9	3.512		
Large	Little tuna	6823	3.0	28.6	5.323		
Pelagics	King fish	6033	2.6	25.3	4. 707	67178	29.38
	Cobia	613	0.3	2.6	0.478		
	Spotted shark	13217	5.8	46.2	8.593		
Small Pelagics	Indian mackerel	14708	6.4	17.1	3.187	70448	30.81
	Spined anchovy	55740	24.4	65.0	12.080		
Demersal Fish	Charcoal grouper	2826	1.2	9.2	1.715		
	Snapper	4930	2.2	14.7	2.735	11724	5.13
	Gold band fusilier	3968	1.7	13.9	2.580		
Multi-species	Other kinds	61552	26.9	100.4	18.673	61552	26.92
Crustacean	Painted spiny	122	0.1	0.9	0.169		
	lobster	1624	0.7	8.3	1.549	1918	0.84
	Shrimp	172	0.1	0.2	0.037		
	Crabs						
Cephalopods	Cuttlefish	15679	6.9	36.5	6.796	15685	6.86
	Octopus	6	0.0	0.0	0.003		
Sea Cucumber	Sea cucumber	29	0.0	0.1	0.025	29	0.01
Multi-species	Other kinds	121	0.1	0.1	0.016	121	0.05
Total	Total	228,655		537.8			

CHAPTER 3

Materials and methods of fisheries monitoring case studies

3.1. Introduction

It is needed to develop a novel approach to monitor small-scale fisheries in developing countries, especially tailored for Yemen. Here, two small-scale fisheries from the Red Sea were selected for case studies on monitoring small scale-fisheries in Yemen with the use of the novel approach developed in this study. At first, climatological and environmental parameters governing the Red Sea are reviewed. Environmental parameters on the fishing grounds of the two fisheries were derived from remotely sensed data because observations of marine environments using research vessels aren't conducted in Yemen. These environmental parameters remotely sensed with satellites are freely available via the internet. Finally, it is explained how catch and position data of fishing boats were acquired in a participatory monitoring involving fishermen and co-workers in Yemen.

3.2. Climatology

3.2.1. Wind regime

Large-scale wind patterns in the Red Sea are dominated by the seasonal monsoon reversal and the surrounding orography (Patzert, 1974, Clifford et al., 1997 and Sofianos and Johns, 2003). North of about 19–20°N, winds blow from the northwest year-round, but farther south, the wind direction and intensity depend on the Arabian Sea monsoon. During the Northeast Monsoon in winter (typically November to April), winds blow from the southeast in the southern Red Sea. During the Southwest Monsoon (June to September), winds blow predominantly from the northwest along the entire Red Sea (Murray and Johns, 1997; Ralston et al., 2013). Surrounding coastal mountains channel near-surface winds such that monthly mean wind vectors are largely parallel to the long axis of the basin. The seasonal, along-axis winds drive surface currents (Clifford et al., 1997 and Sofianos and Johns, 2003), affect exchange at the sill at Bab el Mandeb Strait (Patzert, 1974 and Sofianos and Johns, 2002).

3.2.2. Currents pattern

Estimates of net evaporation over the Red Sea reach 2 m/year (Morcos, 1970) and the deep hypersaline water, which fills the bulk of the Red Sea, must exit through the Bab el Mandab Strait (Fig. 3.1) as a southward-flowing high density bottom layer. The deep water is widely understood to form in the northern Red Sea, perhaps mostly in winter, influenced by high density outflows from the Gulfs of Suez and Aqaba (Murray et al., 1984; Cember, 1988). This overflow of Red Sea deep water has been tracked spreading over 50° longitude eastward to the coast of Sumatra and over 30° latitude southward to the Mozambique Channel in the Indian Ocean (Wyrtki, 1971), making it an essential element in the thermohaline circulation of the Indian Ocean.

Previous studies in the Strait (e.g. Morcos, 1970; Maillard and Soliman, 1986) indicate a 2-layer exchange flow (Fig. 3.1) with a magnitude varying roughly from a yearly average of 0.3 Sv to a maximum of ~0.6 Sv in winter. Mean salinities and temperatures of the upper layer inflow from the Gulf of Aden and the lower layer outflow of Red Sea water are 36.5 psu and 25°C, and 40.5 psu and 21.5°C, respectively. Indirect hydrographic evidence (Patzert, 1974; Maillard and Soliman, 1986) provides rough estimates of a maximum outflow of Red Sea water through the Strait of 0.57 Sv in winter, decreasing to 12% of winter value in early summer and 6% of winter value by the end of summer. The shift to northwesterly winds in summer over the southern Red Sea is thought to lead to a 3-layer flow pattern with a thin surface layer outflow, a mid-depth inflow, and an attenuated deep-water outflow (Patzert, 1974; Neuman and McGill, 1961). The summer regime in the Strait, however, is dominated by the massive intrusion (equivalent to 1.7 x 10^{12} m^3 volume) of cold (19° C), low salinity (36.0-36.5 psu) water from the Gulf of Aden, which occupies 70% of the water column in July, August, and early September (Murray and Johns, 1997). This annual influx of cold nutrient-rich water apparently is critical to the biological productivity of the southern Red Sea (Souvern-mezoglou et al., 1989).

3.3. Remote sensing and bathymetry data

Sea surface temperature (SST), chlorophyll-a, and bathymetric data were used in this study. Other environmental data, such as wind data, currents data, sea surface height anomaly (SSHA) were not available for the study area. Daily SST data were avilable in most of the days,Although daily chlorophill-a data were also available, weekly composites data of chlorophyll-a were used because of missing data in most of the days due to clouds and minimizing area of missing data. The use of weekly composite data usually does not affect interpretation of environmental condition because of the slow change of chlorophyll concentration in the water.

Environmental data are imported into the ArcGIS (ESRI, Inc., Redlands, CA) using the Environmental Data Connector (EDC) which is an extension of ArcGIS to connect to THREDDS/OPeNDAP servers to import environmental data into ArcGIS. Subsets of the above-mentioned data were used by extracting data of study areas during the study period from the datatsets. Data can be imported as feature or raster data. Feature data were used in case to examine a correlation between environmental conditions and distributions of fishing points statistically. Otherwise, it can be imported as raster data to visualizeenvironmental conditions in the study area.

The Moderate Resolution Imaging Spectroradiometer (MODIS) data of SST (daily) and Chl-a (weekly) between September 2011 and January 2012 (for Indian mackerel) and SST (weekly) between August 2012 and September 2013 (for pharaoh cuttlefish) were imported from the OceanWatch website: (http://oceanwatch.pfeg.noaa.gov/thredds/catalog.xml). The 4-km spatial resolution SST and Chl-a are a science quality data set in the Network Common Data Form (netCDF), which makes it easy to import the data into ArcGIS in the form of raster or feature layers. The different types of satellite data were importedfor two purposes: one was raster format of dataset for investigation of the role of environmental variables on the distribution of fishing grounds, and the other was feature format for extraction og instantaneous values of environmental variables at each fishing location. Details of the datasets used in this study are described below:

3.3.1. Dataset of SST

SST data was based on Aqua MODIS and NPP data with a spatial resolution of 4.4 km during the nighttime (4 micron) with a scientific quality; import of daily and 8-day composite data. These data were an improved version of the near real time SST products.

Water leaving radiances were gathered by the MODIS sensor and processed to sea surface temperature by NASA's Goddard Space Flight Center. Data were processed using an algorithm developed by University of Miami's Rosenstiel School of Marine and Atmospheric Sciences (*Brown and Minnett, 1999*). Information on this processing can be found at Goddard's MODIS-Ocean page (http://modis-ocean.gsfc.nasa.gov/). This processing is being taken over by Goddard's Ocean Biology Processing Group (OBPG).

3.3.2. Dataset of Chlorophyll-a

Daraset of 8-day composite chlorophill-a was based onAqua MODISand NPP images with a spatila resolution of 4 km with a scientific quality.These data were an improved version of the near real time chlorophyll products.

NASA's Goddard Space Flight Center (GSFC) receives raw satellite data. Processing is accomplished using the SeaWiFS Data Analysis System (SeaDAS) software (*Fu et al., 1998*). An atmospheric correction is applied to the data to yield a measurement of water leaving radiance (*Gordon and Wang 1994, Shettle and Fenn 1979*). These radiances are processed to chlorophyll-a concentration using the NASA developed OC3M algorithm (described in *O'Reilly et al. 2000*). This algorithm is analogous to the OC4v4 algorithm used in the processing of SeaWiFS data, but adjusted for the specific bands available on the MODIS sensor. Validation is accomplished by comparison with in situ ocean color measurements. In situ measurements are gathered by buoys as part of the Marine Optical Characterization Experiment (MOCE).

3.3.3. Dataset of Bathymetry

Dataset of bathymetry was based on Global Digital Elevation Models/SRTM30+ Version 6.0 (1 km - Worldwide), (Becker, 2009). The bottom topography data ETOPO1 is a one arc-minute global relief model of Earth's surface that integrates land topography and ocean bathymetry provided by National Geophysical Data Center, United States of America.

3.4. Cooperative research

The voluntary work with fishermen have never been tried on the Red Sea coast of Yemen. Cooperative research with the small-scale fishermen was conducted in four different coastal areas on the Red Sea coast of Yemen. The four areas are located on the southeastern part of the Red Sea coast. They are Al-Hodeidah, As-Saleef, Al-Khawbah and Al-Luhaiyah from south to north with distances to Bab el Mandab Strait of 235, 300, 327, 347 km, respectively (Fig. 3.2). Due to the time limitations of the study, the same scheme was applied to the four areas (though the start time of each study are different) and in cases when a cooperation with fishermen couldn’t be established, other areas were addressed. The fishermen were asked to carry GPS data loggers while fishing and to report the daily catch and effort (number of fishermen). Data on artisanal fishing boats voluntarily participating in the case studies were collected.

3.4.1. Targeted areas

Al-Hodeidah and As-Saleef in 2011

We started the cooperative research with fishermen in Al-Hodeidah (10 GPS loggers) in June 2011 and in As-Saleef (10 GPS loggers) in December in 2011. The target species was the Indian mackerel (*Rastrelliger kanagurta*) in Al-Hodeidah and was the Indian white prawn (*Penaeus indicus*) and green tiger prawn (*Penaeus semisulcatus*) in As-

Saleef. The study in Al-Hodeidah was continued from June 2011 until March 2012 (with some interruptions) while the study in As-Saleef was continued for only two months and then were terminated.

Al-Khawbah

The study in Al-Khawbah (20 GPS loggers) was started in June 2012 and continued for four months before terminated in November 2012. The fishery was pelagic purse seine fishery, mainly targeting the Indian mackerel and some other related species. The study period of four months were divided into two periods: the first two months and the latter two months. The study in the former period was conducted with one co-worker and that in the latter period with another coworker. Although the last coworker had intimate relationship with fishermen, the study was terminated by the end of November 2012 because of the difficulties to establish the cooperation with fishermen in this area.

Al-Luhaiyah

The study in Al-Luhaiyah (40 GPS loggers) was started in June 2012 and continued until May 2014. This study targeted cuttlefish and demersal fisheries. In this study one coworker started working with the local fishermen in May 2012. This work was terminated only after 20 days because of the difficulty in convincing the fishermen to engage in cooperative research. The reasons of failure were the lack of experience of the coworker in working with fishermen and the lack of an intimate relationship with fishermen. From June 2012, another coworker started the work and he continued for two years until May 2014. This study was the most successful among the four trials and this is may be because the coworker was a fisherman and has a strong relationship with most of the participating fishermen in this study.

3.4.2. Role of coworkers

It is uncommon among fishermen in the study areas to encounter scientific researchers. Moreover, the low awareness of fishermen of the scientific research raised their suspects. They suspected that their data may be used against them or may be disseminated to third parties for commercial purposes. This has led to difficulties in establishing a cooperation with fishermen in the data collection. The coworker is the person who is going to be in charge of collecting the data and deliver the loggers regularly. His character and relation with the fishermen is important in pursuing the research. Dealing with fishermen usually need to convince them about the objectives of the research and reassure them about the ways their data will be used. It is also important of the coworker to be insistent when dealing with people like fishermen. These features were available in the coworker in Al-Hodeidah and to a less extent in the coworker in Al-Luhaiyah and this was resulted in successfully continuing data collection for longer period.

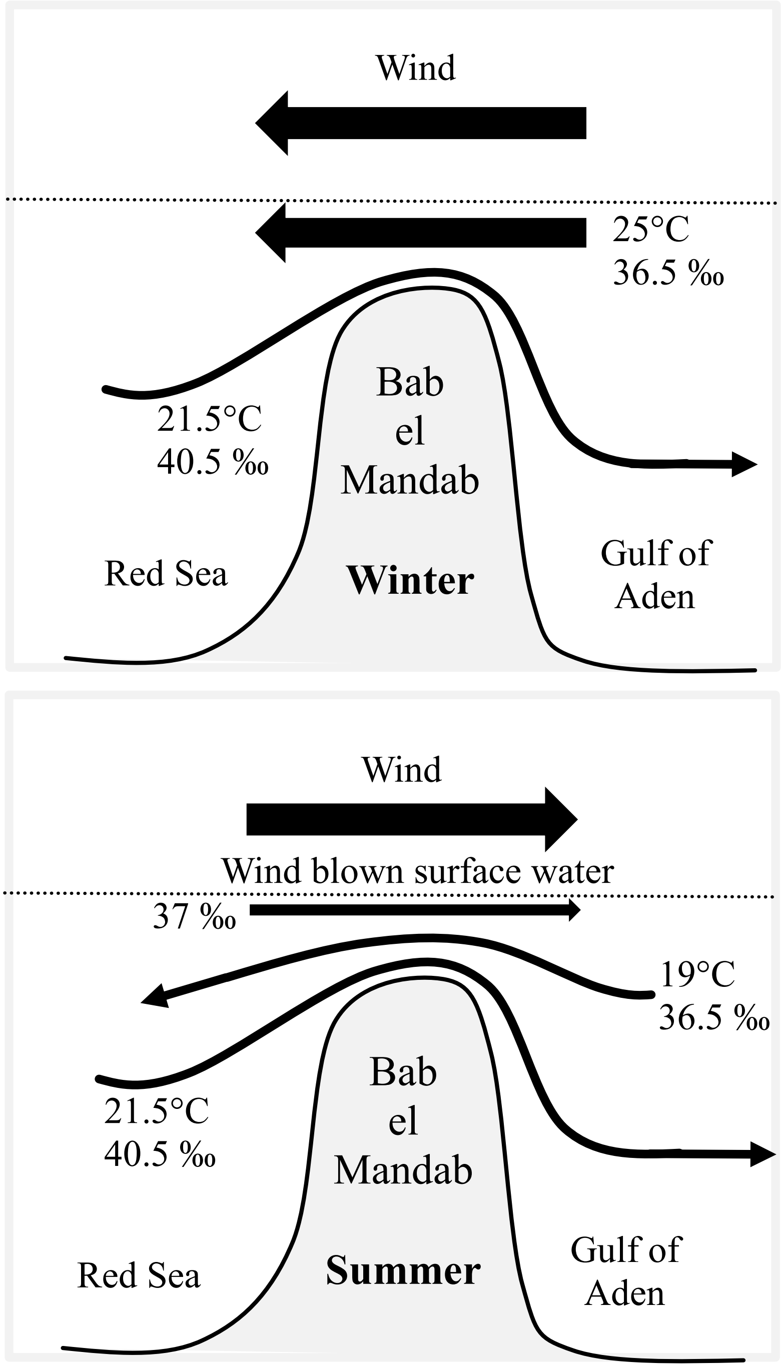


Fig. 3.1. Circulation pattern at Bab el Mandab Strait

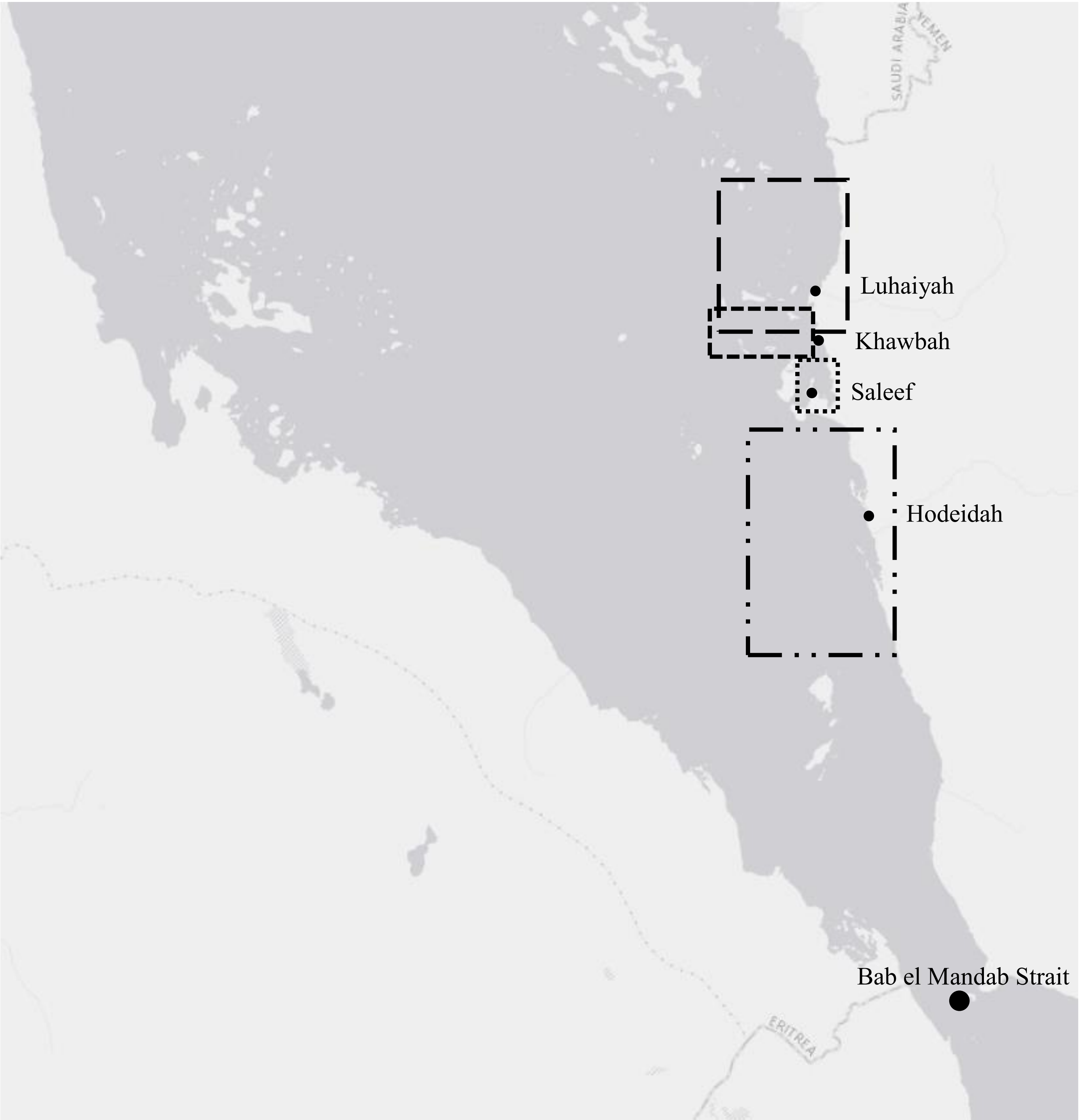


Fig. 3.2. The four study areas where the cooperative research was attempted. The studies targeted the Indian mackerel in Hodeidah, shrimp fisheries in Saleef, purse seine fishery in Khawbah and cuttlefish and demersal fisheries in Luhaiyah.

CHAPTER 4

Small-scale Indian mackerel fisheries in Yemeni Red Sea

4.1. BACKGROUND

Advances in global positioning systems (GPS) technology make it possible to acquire highly accurate data in rapid succession and in continuous time, providing new opportunities to aid the research, management and conservation efforts of fisheries resources (Bertrand and Lengaigne, 2008; Saitoh *et al.*, 2011). For example, GPS data can be used to show the distribution and extent of fleet activity and can be developed and reported as an indicator of fishing effort. It can also be integrated with reported data on catch and effort to give high spatial resolution data on catch and catch per unit effort (Anon, 2010). Tracking of fishermen behavior, the fishing activity and the target species behavior all together are important aspects in the conservation and management of fisheries resources. The use of GPS data loggers will contribute to our understanding of these aspects to be integrated in planning for future fisheries management of the resources.

The Indian mackerel fishery is the largest in the Red Sea of Yemen in terms of volume of the landed catch. It accounted for 30.4% (7,300 ton, statistics of 2007) of total landings of the Red Sea coast of Yemen in 2007 (Alabsi and Komatsu, 2014). Management measures do not exist for this species except the prohibition on the use of light (fish aggregating devices (FADs)) during fishing. Thus, it is important to investigate fishing activities for Indian mackerel, estimate the CPUE and explore the variables contributing to fishing ground formation.

The short-term influence of the environment is largely dominated by its effects on the behavior, distribution, and hence catchability of the fish. In contrast, medium- and long-term effects are mainly reflected in the mortality and growth of young fish, which translate into interannual or interdecadal changes in abundance (Fréon, 2005). Our focus here is the first type, the short-term influence of the environmental variability on the Indian mackerel distribution and catchability on a scale of a few days to a few weeks.

Cooperative research was conducted with fishermen to characterize the fine-scale, spatio-temporal dynamics of schooling behavior in Indian mackerel (*Rastrelliger kanagurta*) and the environmental variables which control the spatio-temporal distribution of fishing grounds.

Specific objective of the study was to develop a novel approach to monitor small-scale fisheries such as Indian mackerel fisheries. This method consists of monitoring of boat positions with GPS devices, obtaining catch data at a port, plotting fishing positions with catch data, analysis with GIS, estimating CPUE, and analyzing fishing ground formation with GIS and remote sensing data. This approach is adjusted to Indian mackerel fisheries by combining the use of GPS data loggers with catch data to: (1) describe the coincident characteristics of purse seine operation method, and related operation indices; (2) obtain CPUE from the individual hauls and from the whole fishery; (3) investigate formation of Indian mackerel fishing grounds in relation to environmental variables acquired by remote sensing and GIS and (4) compare the spatial distribution of aggregations and fishing activities to the known spawning time of mackerel.

4.2. MATERIALS AND METHODS

4.2.1. Study area

This study was conducted in the southeastern Red Sea coast (14°10'–15°03'N and 42°32'–43°00'E) (Fig. 4.1), offshore of Hodeida, the main city on the Red Sea coast of Yemen. The fishing boats operating from the main landing site target different types of pelagic and deep-water species. Indian mackerel fishing boats operate all year round except during the lunar period of every month or during the windy days in the winter.

4.2.2. Target species

FAO (2001) reported that the size at first maturity of *R. kanagurta* was 20 cm, whereas in the Malacca strait was 17 cm (Hariati *et al.*, 2005), while in the Java Sea was 18.25 cm (Atmadja *et al.*, 2003). Bal and Rao (1984) have summarized the literature on the food and feeding habits of *R. kanagurta*, based on observations from the Indian waters. They found that this species, like the sardines, feed on both phytoplankton and zooplankton strained from the surrounding waters by the well developed feathery gill rakers borne by the gill arches. The feeding habits of the Indian mackerel appear to change with size from a purely herbivorous diet in juveniles to a combination of zooplankton and phytoplankton in adults.

Rao (1962) studied the food habits of mackerel (24 –32 cm size) from offshore areas in drift nets operated off Vizhinjam, south coast of India, and found feeding to be lowest during October to December coinciding with peak spawning activity. Madhupratap *et al.* (1994) concluded that in species such as *R. kanagurta*, spawning may occur in inshore waters with abundant food. Spawning was reported to occur twice a year, once between

October and December in the east and west coast of India (Rao, 1964). In Malacca strait in Indonesia, peak spawning season was reported to occur in September-November period (Oktaviani *et al.*, 2014). Merret and Thorpe (1965) found that the spawning of Indian mackerel took place between September and March in the East African waters. Differences in the timing of spawning in different areas indicate that the Indian mackerel, like many other species, adapts its life cycle to spawn where the environmental factors are optimal for spawning.

A recent study on age and growth of the Indian mackerel from the Red Sea coast of Yemen indicated that oldest males and females were four years old and age group II was dominant in the catch for both sexes. The study concluded that *R. kanagurta* in the Yemeni coast of Red Sea becomes fully recruited to the fishery at an age of two years (Al-Mahdawi *et al.*, 2010).

For small pelagic fish like Indian Mackerel, adults aggregate to spawn and fertilize their eggs. The eggs hatch into pelagic larvae that drift and disperse with the currents to nursery areas where they feed and grow (BOBLME, 2012).

4.2.3. Description of cooperative research

Cooperative research was conducted with artisanal fishermen from a fishermen community involved in Indian mackerel fishery offshore of Hodeidah, on the Red Sea coast of Yemen to deploy portable GPS data loggers (Holux M-241 Bluetooth Data Loggers; 20 devices) and record fine-scale movement patterns of Sanbouk boats (12-15 m in length) from fishing trips for Indian mackerel in the period from May 2011 to January of 2012. The participants were asked to provide fishing trip report and to operate GPS loggers to record the location of fishing activity.

4.2.4. Data loggers

Holux M-241 Bluetooth Data Loggers were used. These were small and easy to use and the battery capacity (typically ~14 hours use) is ideal for one-night trips of the Indian mackerel fishery. The internal storage capacity is adequate for recording approximately 130,000 waypoints equivalent to 166.7 fishing hours (13.9 fishing days) of data at a logging rate of 5-seconds. PC based software called “Holuxlogger Utility” was used to configure the receivers and download the data. The GPS loggers create a data file for each logging operation (daily). The use of the logger required the fishermen to turn the device on and off at the start and end of the fishing trip, respectively. Rechargeable battery were used and hence required to be recharged after every trip; however, the data were downloaded to a PC once a week.

4.2.5. Data collection

The study used 20 GPS devices, which were deployed on 20 fishing boats. However, some of the participating fishermen did not show cooperative attitude and started misreporting the catches and/or turn off the loggers while fishing. Since those fishermen were excluded, the study was continued with a smaller number, 10 fishing boats for the remaining period of the study. During the first four months, which was a training period, the catch data were not used for analysis due to the high uncertainty in the reported catches. However, locations of the fishing activity were used in the analysis. There was a coworker in the landing site, whose role was to collect the loggers after every trip and receive the catch data. Later, the catch report data are saved in excel files. The fishing activity was observed using GPS data loggers for 7 to 10 days a month from the start of the fishing schedule after the end of the lunar period, which usually starts from the day

18 of every lunar month. The loggers were given to the fishermen in the afternoon before their departure and everyday the battery are replaced with recharged ones and once a week the data are downloaded from the loggers to a PC.

4.2.6. Data Types

4.2.6.1. Indian mackerel fishing data

GPS logger data

GPS logger devices collected the boat location (latitude and longitude), vessel speed in km/hour, distance travelled, date and time. These data are recorded continuously during the whole trip at 5-seconds interval. It was intended to capture the fine scale nature of fishing activity and especially the purse seine operation method.

Catch characteristics

Catch data were collected on every trip upon arrival at the landing site and this includes catch composition by species and weight (number of baskets, one basket = 35Kg), number of fishermen, and haul numbers (how many times the net was deployed). In case of the Indian mackerel, its catch weight was recorded as the number of baskets, and later converted into kilograms. However, sometimes there was a bycatch of large pelagic species, such as yellow fin tuna, skipjack, cobia, etc., and in this case, their weight was recorded as kilograms.

Boat and net characteristics

Boat and net characteristics data were collected only one time during the study period. The boat data were name of the owner, type of the boat, overall length, width and depth of the boat. The net characteristics data were net type, length, depth and mesh size.

4.2.6.2. Remote sensing data

See the third chapter for a description of the different remote sensing data sets used in this study and the procedures to import them into ArcGIS.

4.2.7. Data analysis

Fishing data were analyzed using ArcGIS 10.0. Each KML file of a single trip was first imported into ArcGIS, tracks were browsed to detect the haul locations, and then the related catch and effort data were matched. Catch/boat/day and catch/haul were estimated from the reported catch and effort data. We excluded certain types of data in several cases:

1. Hauls from May until August in 2011 were excluded from the calculation because of the high uncertainty of catch reporting.

2. Hauls where the catch was composed of mixed species and the quantity of the bycatch was more than the quantity of the target species (Indian mackerel), were also excluded. A total of 134 hauls of this type were excluded.

3. Zero catch hauls (accounted for 23% of the total hauls) were also excluded.

In this later case (case no.3), the data were included in the calculation of CPUE, but were not included in fishing grounds-environment analysis (fishing locations were correlated with SST and chlorophyll), because the purpose of the study was to investigate the environmental factors responsible for productive fishing grounds.

Values of environmental variables of SST (daily night image), chlorophyll-*a* (8-day composite) and sea bottom depth of each individual fishing location (haul) were extracted from the environmental datasets. Fishing data were processed thoroughly to extract many characteristics related to the operation method of purse seine for Indian mackerel. These analyses include:

Fishing trips descriptors. They consisted of data describing the general aspects of fishing trips and these included trip length in hours, departure and return times, working days and halting days.

Fishing operation. They consisted of more detailed information on the fishing operation such as search time before net deployment, number of hauls per day, after-haul drifting time, drifting speed, drifting direction, catch per day, catch per haul, catch per day per boat, etc.

Hauling descriptors. They consisted of information describing the hauling (deployment of the net and encircling of fish school) and these data included hauling or encircling duration (time between start and end of hauling), hauling speed, haul size (diameter in meters) and observed vs. reported number of hauls.

4.2.7.1. Identification of purse seine fishing hauls

Each KML file containing the GPS data of a single fishing trip was first imported into ArcGIS. Tracks of each trip were visualized and checked for the locations of fishing hauls, which appeared as big circles in the trip route. Next, each circle was verified whether it was really a fishing activity or not. This was done by checking the after-haul speed, in case it remained slow for a long time, more than 10 minutes, then it should be a fishing haul. If the speed continued high after the haul, then it was not a fishing haul. The speed profile of each fishing trip showed more clearly this operation, which is usually associated with continuous high speed of the boat while searching for Indian mackerel schools, followed by increased speed for a short period of about one minute in average, which was corresponded to the hauling (encircling of the fish school with the net). Finally, after the haul, the boat engine was turned off and the boat was left drifting. This was clearly shown in the low speed after hauling which extends for a long time, between 15 minutes and 2 hours, during which the fishermen took the fish out of the net and prepare the net for the next fishing operation. This rhythm of three stages (searching-hauling-drifting) continued in the speed profile for each fishing haul during the trip. Fig. 4.2 shows an example of a complete navigation route of one of the fishing trips and Fig. 4.3 shows the identified locations of all the fishing hauls conducted in one single trip. Fig. 4.4 shows an enlarged image of one of the fishing hauls.

4.2.7.2. Calculation of the catch per trip ($CPUE_{trip}$) and catch per haul ($CPUE_{haul}$)

The fishermen were asked to report the catch for each fishing haul, but with their busy schedule they could not provide us the catch per haul. Instead, they reported the catch for the whole trip, while they usually conducted several fishing hauls in every trip. One good feature of the hauls’ locations was that most of the hauls conducted in the same day by one boat tended to be located close to each other. In such cases, it was assumed that the whole area belonged to the same fishing ground. In this case, the catch of the whole day of a single fishing boat was divided among all the hauls conducted in that day to obtain the catch per haul.

The catch from all fishing boats during the month were summed. Then, the sum were divided by all the fishing days of the corresponding boats to obtain the catch per trip ($CPUE_{trip}$) and by all the fishing hauls of the whole month to obtain the catch per haul ($CPUE_{haul}$).

$CPUE_{trip}$ = total catch / no. of fishing days;

$CPUE_{haul}$ = total catch / no. of fishing hauls

Total catch = total catch of all voluntary fishing boats of the whole month;

Fishing days = all fishing days of all voluntary boats of the whole month;

Fishing hauls = all fishing hauls of all voluntary boats of the whole month

4.2.7.3. Data visualization

The identified fishing locations of Indian mackerel during the whole study period from May 2011 until January 2012 were visualized to show the spatial and temporal distribution of fishing activity. The locations of fishing hauls were superimposed on bathymetric maps, 8-day chlorophyll images and one-day SST images. Fishing locations and catch per haul were explored against these different environmental variables and correlations were drawn. Frequency distribution of SSTs and Chlorophyll-*a* at the fishing locations were prepared to investigate their range in the fishing grounds and the optimal range in different months during the study period.

4.3. RESULTS

The 5-seconds intervals of the recorded position data with GPS, which had a very high spatio-temporal resolution, enabled fine scale mapping of the fishing activity. Fig. 4.2 shows a complete route of a typical fishing trip with different types of the recorded data shown on the navigation route. Given the short time of hauling which in most cases as short as 1-minute, all locations of hauling purse seine activity were identified accurately with 5-seconds intervals. Fig. 4.3 shows a sample of the identified haul locations in one of the trips.

4.3.1. Purse seine fishing effort indices

Twelve fishing boats participated in the study and their overall length ranged between 12 and 15 m with an average of 13.1 m. All the boats used outboard engines of 40 (n=4) or 75 (n=8) hp and purse seine nets, of which the lengths ranged between 340 m and 600 m with an average of 407 m. Net depth ranged from 15 to 20 m with an average of 16.3 m and net mesh size of 2 cm. The fishing activity occurred only at nighttime between sunset and sunrise times. Fishing usually started from the day 20 of every lunar month and continued until the day 7 of the next lunar month. Fishing activity for Indian mackerel usually halted every month during the lunar period.

The time distribution during the trip indicated that the time budget was distributed among three main activities: travelling, searching, and drifting. A sequence of searching, hauling and drifting occurred in every operation of purse seine haul. The sequences were important indicators about the fishing activity. Searching for fish took most of the time spent during the trip. Search time indicates the time spent in searching for Indian mackerel schools and it is an indicator of the effort made to locate the fish schools and the more time spent in this activity the less abundant the fish are. Search time ranged from 00:01:30 to 4:28:50 (hh:mm:ss) and averaged 00:52:55±00:59:18 (Fig. 4.5). Drifting time (or after-haul drifting time) was defined as the time during which fishermen processed the catch and prepared the net for the next fishing operation. The length of searching time was longer than drifting time. During the drifting time, the fish inside the net or entangled in the net were collected and stored. Drifting time ranged from 00:08:25 to 2:35:45 with an average of 00:40:51±00:22:25 (Fig. 4.6).

4.3.2. Purse seine hauling descriptors

Hauling duration, which was defined as the time between the start and end of hauling, was the shortest and this is because the hauling operation is conducted at high speed and in short time to encircle the fish school and to increase the fishing efficiency. Fig. 4.7 shows distribution of hauling duration and indicates that purse seine hauls ranged from 0:00:30 to 0:01:55 minutes with an average time of 0:01:02±0:00:16 (most hauls took between 0:00:50 and 0:01:20). Frequency distribution of haul timing (time during the night) according to month is shown in Fig. 4.8. Hauling time occurred between 17:00 and 6:00 a.m. and most of the hauls occurred between 19:00 p.m. and 2:00 a.m. No fishing activity was recorded during the daytime and this indicates that the fishing activity is only conducted at night and extended between sunset and sunrise times. We used 542 hauls in the analysis and fishing boats conducted between 1 and 7 hauls/trip with an average of 2.65±1.4 hauls/trip (trip=one night). The number of hauls/trip when plotted against the catch/trip, the catch/trip increased with increasing number of hauls during a trip (Fig. 4.9, above). Frequency distribution of number of fishing hauls per trip indicated that in most trips, fishermen conducted 2 hauls, 1 haul, 3 hauls and 4 hauls per trip, which accounted for 30.1%, 24.3%, 19.9% and 13.1% of all trips, respectively (Fig. 4.9, below).

Hauling speeds were analyzed to investigate their effect on catch per haul. Fig. 4.10 (above) shows frequency distribution of hauling speeds, indicating that most of the speeds ranged between 11.5 and 15.0 m/s. Catch per haul overlaid on hauling speed distribution is shown in Fig. 4.10 (below). While hauling speeds between 14.5 and 15.0 m/s accounted for the highest frequency, the highest catch/haul (averaged 202.5 Kg/haul) was harvested from hauls which has relatively lower speeds between 13.5 and14.0 m/s. Speeds between 14.0 and 14.5 m/s accounted for the second highest catch/haul with an average of 143.7 kg/haul.

4.3.3. CPUE$_{trip}$ and CPUE$_{haul}$ of purse seine for Indian mackerel

The CPUE$_{trip}$ and the CPUE$_{haul}$ for the whole period are shown in Table 4.1. The catch per trip did not differ significantly among the months except January for which the number of hauls was small (28 hauls). However, the catch per haul differed significantly among the months and was highest in September with an average of 125.7±56.7 kg/haul and was lowest in November with an average of 69.2±50.4 kg/haul. The high standard deviation of CPUE calculations arose in part from the high number of hauls with zero catch which accounted for 23% of total hauls.

4.3.4. Mapping of fishing locations

The identified fishing locations (haul locations) and the locations of the calculated CPUE$_{haul}$ for the whole study period are shown in Fig. 4.11 (left) and Fig. 4.11 (right), respectively. Fishing locations in October differed significantly from the other seven months for which the data were available. The locations were concentrated in two semi-enclosed bays near the coast. The fishing activity was relatively spatially distributed in September and November while occurred relatively closer to the coast in December and January due to the strong winds during this period. The fine scale analysis of the locations of hauling in single days or in several subsequent days revealed that the locations tended to concentrate in specific locations.

4.3.5. Fishing grounds distribution and environmental variables

Chlorophyll-*a* concentration at the hauling locations was significantly high in October compared to other months and it reached a peak of 13.42 mg m^{-3} with an average of 7.97±3.77 mg m^{-3}. The optimal chlorophyll-*a* concentration in October had a range from 5.78–13.42 mg m^{-3}, averaged 8.91±3.03 mg m^{-3} (contributing to 66.3% of the total sampled catch in October). Comparing the high, medium and low averages of both SSTs and chlorophyll-*a* concentrations with their corresponding catches shows that chlorophyll-*a* concentration was an important determinant of Indian mackerel distribution. Relatively higher catches were obtained from waters with higher chlorophyll-*a* concentrations. Fig. 4.12 shows Indian mackerel fishing locations overlaid on weekly composites of chlorophyll-*a* imagery. It showed a noticeable trend of concentration of hauling locations in high chlorophyll-*a* waters. The highest chlorophyll-*a* concentration in October was associated with significantly different distribution of fishing activity compared to other months. Indian mackerel locations were concentrated in semi-enclosed bays near the coast synchronized with peak chlorophyll-*a* concentration. Fig. 4.13 shows the catch/haul of high, mid and low averages of both chlorophyll and SST during the different months of the study period. Averaged chlorophyll-*a* concentration had some steady positive impact on CPUE (catch/haul) during the study period, while SST had a positive impact on CPUE only in October and January. Fig. 4.14 and Fig. 4.15 show chlorophyll-*a* and SST frequency distribution at hauling locations in different months of the study period.

Indian mackerel hauling locations were overlaid on SST images and the mackerel locations were highly aggregated around the SST fronts (Fig. 4.16). To analyze the combined effect of SST and chlorophyll-*a* on Indian mackerel distribution, hauling locations were superimposed on SST images which showed clear SST fronts and 0.4 mg m^{-3} chlorophyll-*a* gradient contours were overlaid. Hauling locations were found to concentrate along SST fronts and in relatively high chlorophyll waters (Fig. 4.17).

Indian mackerel fishing locations occurred in limited bathymetric range of mostly less than 25 m. Fishing locations were distributed at relatively shallower bottom depths in September (8.6±6.4 m) and October (6.2±4.9 m) and relatively deeper bottom depths in May-August (23.9±14.9 m), while were distributed at relatively middle bottom depths in November, December and January with an average bottom depths of 13.5±7.1 m, 10.3±4.1 m and 13±6.4 m, respectively. Fig. 4.18 shows bathymetry distribution of Indian mackerel fishing locations in different months. All fishing spots for Indian mackerel (Fig. 4.19, right) and only high catch fishing spots (>350 kg/haul) (Fig. 4.19, left) were overlaid on bathymetry maps. Most of fishing locations were concentrated in an area with shallow bottom depths.

4.4. DISCUSSION

4.4.1. Fishing grounds formation in relation to environmental variables

For rational management of small pelagic fish, we need to understand the variables which affect the spatio-temporal distribution of their fishing grounds. Movement of pelagic fish is expected to be driven by their environmental preferences and food requirements (Fréon *et al.,* 2005). Although investigation of both sea surface temperatures and chlorophyll-*a* at hauling locations did not show a good correlation with CPUE. However, concentration of hauling locations at specific areas on a daily basis and sometimes in several consecutive days was noteworthy. For this purpose, careful observation and analysis of hauling locations on a daily basis overlaid on daily SST images have shown a trend of concentration of hauling locations along the SST fronts, i.e., around the boundaries of two water masses of different temperatures.

Near real time satellite thermal images are quite commonly used by pelagic fishing fleets in an attempt to locate the best fishing spots (Santos, 2000). Anchovy spawning is thought to be related to certain temperature ranges (Lasker *et al.*, 1981; Fieldler, 1983; Richardson *et al.,* 1998; van der Lingen *et al.*, 2002) and in the North Sea, herring biomass distributions seem to be related to SST and salinity, with greater densities often associated with strong gradients in these parameters (Maravelias and Reid, 1995). A similar association of anchovy, sardine, and jack mackerel distributions with thermal fronts was demonstrated in northern Chile (Castillo *et al.*, 1996). In Côte d'Ivoire, pelagic fish catches were related to a pattern of SST at particular lags of a few weeks, which was associated with enrichment in zooplankton, as fish tend to be more abundant in newly productive areas (Mendelssohn and Cury, 1987).

In addition to the SST, chlorophyll-*a* was an important determinant in the formation of fishing grounds. Most of fishing locations occurred in high chlorophyll-*a* waters and CPUE was relatively higher in high chlorophyll-*a* waters. Moreover, the inshore movement of Indian mackerel during the highest chlorophyll-*a* concentration in the year and the high chlorophyll-*a* concentration in waters where mackerel found in all months have its implications. It indicates a tendency of this species to stay in waters with relatively high chlorophyll-*a* concentration. Because they are plankton feeders, they respond very rapidly to plankton blooms attributable to environmental variability.

The formation of fishing grounds and the success of pelagic fisheries are largely dependent on these short-term influences, e.g., SST and Chlorophyll-*a*, that mainly affect the catchability and availability of fish to the fisheries. When catchability of a stock increases, abundance of the stock reduces. However, catch rates do not respond immediately because fish continue to aggregate in schools eventhough their abundance is reduced (Fox, 1974; MacCall, 1976; Ultang, 1976; Mackinson *et al.*, 1997; Fréon and Misund, 1999). Therefore, for future monitoring of abundance of pelagic fish, time series of CPUEs must be used from the whole fisheries on Indian mackerel in the Red Sea, because it is possible that the catch may remain stable and will not reflect the real state of the resources in local areas.

The distribution of Indian mackerel fishing grounds was affected by a matrix of environmental variables, i.e., chlorophyll-*a* concentration, SST fronts and bottom depths. Since abundances of small pelagic fish witness highly interannual variations, it is necessary to monitor environmental variables in the mackerel fishery to better understand their effect on mackerel abundance. It may also help us to understand the ecological roles that forage fish play in the marine environments (Fiorentino *et al.*, 2013).

For the purse seine fishery targeting the Indian mackerel, most of the expenditure goes for fuel costs for fishing boats because in this fishery skippers needs to search the sea for fish schools. In case information is given to the fishermen in advance about the potential fishing zones, this will greatly minimize search costs and the time spent in the sea. However, this should be done within a management scheme in which information about potential fishing zones are disseminated to the fishermen and in turn, fishermen comply with the management measures imposed on the fishery.

4.4.2. Spatio-temporal distribution and spawning of Indian mackerel

Fishing locations for Indian mackerel were shifted to inshore waters in October. Fishing occurred inside two semi-enclosed bays and this did not happen in the other eight months. Moreover, chlorophyll-*a* concentration was the highest during this month (October) especially near the coast where the Indian mackerel fishing locations were concentrated. This implies some specific behaviour of Indian mackerel spatially and temporally synchronized with the peak in chlorophyll-*a* concentration in October.

Previous studies of spawning of this species in the study area are lacking. However, interviews with fishermen indicated that this species spawn all year round with two peaks in spring and in winter. Rao (1962) studied the food habits of *R. kanagurta* and found feeding to be lowest during October to December coinciding with peak spawning activity. Low food intake during the peak spawning is a common feature in fishes. This indicates that inshore movement of mackerel, synchronized with the peak chlorophyll-*a* concentration, is less probably related to feeding of adult fishes, but otherwise may be related to peak spawning activity of this species and the availability of feeding requirements of larvae.

The match-mismatch hypothesis of Cushing (1990) attributes successful recruitment to the availability of prey for larvae. Other evidences indicate that physical transport may adversely affect survival rates of larvae resulting in the loss of offspring and low survival rates due to the transport of larvae away from suitable areas for first feeding and/or nursery habitats (Peck *et al.*, 2012). Therefore, for successful recruitment, availability of prey for first larval feeding must be combined with retention of larave within spawning sites. The Indian mackerel in the study area was concentrated in inshore waters inside semi-enclosed bays during the spawning time in October and this was associated with the highest chlorophyll-*a* concentration. Madhupratap *et al.* (1994) concluded that in species such as *R. kanagurta*, spawning might occur in inshore waters with abundant food. This implies that spawning of the Indian mackerel was synchronized during the best time to encounter enough food for the larvae and occur in protected habitat to ensure high retention and survival rates of the resulting offspring.

To examine the environmental conditions in the coastal areas for the whole year and in the past, chlorophyll-*a* concentration obtained by remote sensing was examined for 12-years period from 2003 up to 2014. The result of this analysis indicates that the chlorophyll-*a* concentration peaked in October of every year and October had the highest chlorophyll concentration during the whole year in ten years among the twelve years period and was the second highest during the other two years.

The high consistency of chlorophyll-*a* maximum around October of every year may be attributed to local upwelling induced by the prevailing winds, which blows over the southern part of the Red Sea from October to April. Moreover, water exchange through Bab el Mandab Strait during the summer-time (July to September) is dominated by massive inflow of Gulf of Aden deep water into the Red Sea and until September, it occupies 70% of the water column in the southern Red Sea (Murray and Johns, 1997; Ralston *et al.,* 2013). In the Red Sea, strong stratification during the summer season hinders the possibility of vertical mixing. Wind reverse its direction around October and this is associated with strong wind speed blowing from the north-west and initiate upwelling and enrichment of coastal waters with nutrients (Acker *et al.,* 2008; Raitsos *et al.,* 2013). Investigation of the strength and timing of this phenomenon will help us to understand the environmental variability and the subsequent fluctuation in fish recruitment.

The match of spawning time with the optimal time and location for spawning is expected to result in high survival rates of larvae. If this was the case, it is expected to notice high catches of Indian mackerel in the subsequent years. The time lag between survival success of larvae and the recruitment success as an apparent increase in catch rates of Indian mackerel will depend on the time needed for Indian mackerel to reach the fishing size to enter the fishery. The dominant age group in the catch of the Indian mackerel from this fishery is age group II (Al-Mahdawi *et al.*, 2010) meaning that the age group consists of individuals between two years old and less than three years old. This is the time lag between larval recruitment success and future high catch rates of Indian mackerel. According to inquiry to the fishermen on the catch rates of purse seine fishery of Indian mackerel during the last three years from 2012 to 2014, their answers indicated that catch rates in 2014 was exceptionally high compared to the previous two years. Therefore, it is considered that the 2014 increase in catch rates is due to the recruitment success occurred in 2011.

This study highlights the importance of monitoring of the spawning activity and the corresponding environmental variables for better understanding of fluctuations of future fish abundance. Moreover, it reveals that recruitment success and survival rates can be highly variable among different years and need to be monitored regularly to be able to predict future trends in stock abundance and to decide safe catch levels. For rational management of this species and other pelagic species, remote sensing derived data can contributes valuable information, which can help us to understand the environmental variability and its effects on spawning and recruitment success of this species. Based on this information we can predict how successful larval recruitment may be in regards to the dominant environmental conditions around the spawning time.

Assuming spawning period of Indian mackerel is synchronized with the maximum chlorophyll-*a* concentration in shore waters, it is also possible to predict the spawning time by using remote sensing data, and also to set fishing ban in inshore spawning grounds during the peak spawning period of Indian mackerel, namely occurrence period of the maximum chlorophyll-*a* concentration in shore waters.

4.4.3. Purse seine operation descriptors and indices

The combined use of GPS loggers and catch reporting has enabled the investigation of purse seining at great depth and fine scale and the collected GPS data described many unprecedented indices of small scale purse seining. The 5-seconds logging rate of GPS enabled 100% characterization of purse seine hauls. Fishing effort indices of purse seining can be described using several related indices of purse seine fishing gear. Search time, which represents the time spent in searching for Indian mackerel fish schools, can be used as an index of fishing effort. The number of fishing hauls per trip is another index of purse seine fishing effort. Not all fishing hauls were successful in targeting the fish school and 23% of hauls yielded zero catch. The catch/trip has increased steadily with an increase in the number of hauls conducted during the trip. This represents a strong incentive for fishermen to continue fishing longer to harvest more fish. Therefore, controlling of trip length can be used to restrict the fishing activity in future if deemed necessary to manage the fishery. Hauling speed indicated the optimum speed for best fishing efficiency. Fishermen were found to encircle the fish schools at speeds ranging from 11.0 to 15.5 m/s while the optimal speed was 13.5-14.0 m/s. Haul size, represented by the haul diameter in the GPS data, is an important index of fishing effort as the haul size relates well with the length of fishing gear. Purse seine indices such as search time (area searched), number of fishing hauls and haul size are important information to be used in abundance estimation of this species. For example, it is important to know the search time as it is expected to be well correlated with fish abundance as less search time means higher fish abundance and vice versa.

Figure 4.1. Map showing the study area and the fishing ground of Indian mackerel (ellipse) off Hodeidah, the main city on the Red Sea coast of Yemen.

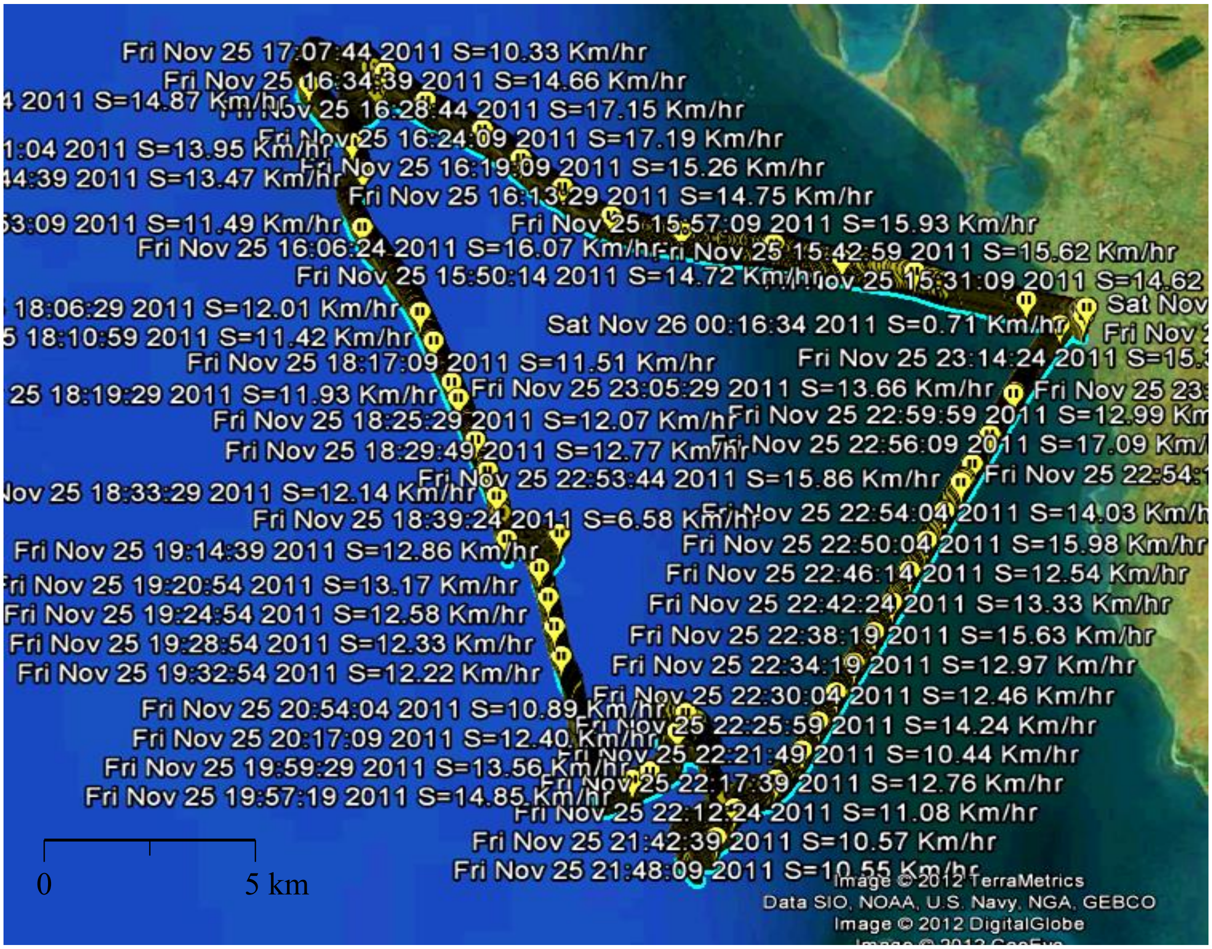


Figure 4.2. Map showing a complete route of a fishing trip from departure to return to the fishing port on land. Data points recorded at 5-seconds intervals together with speeds, times and dates obtained by a GPS logger (Map data: Google, GeoEye).

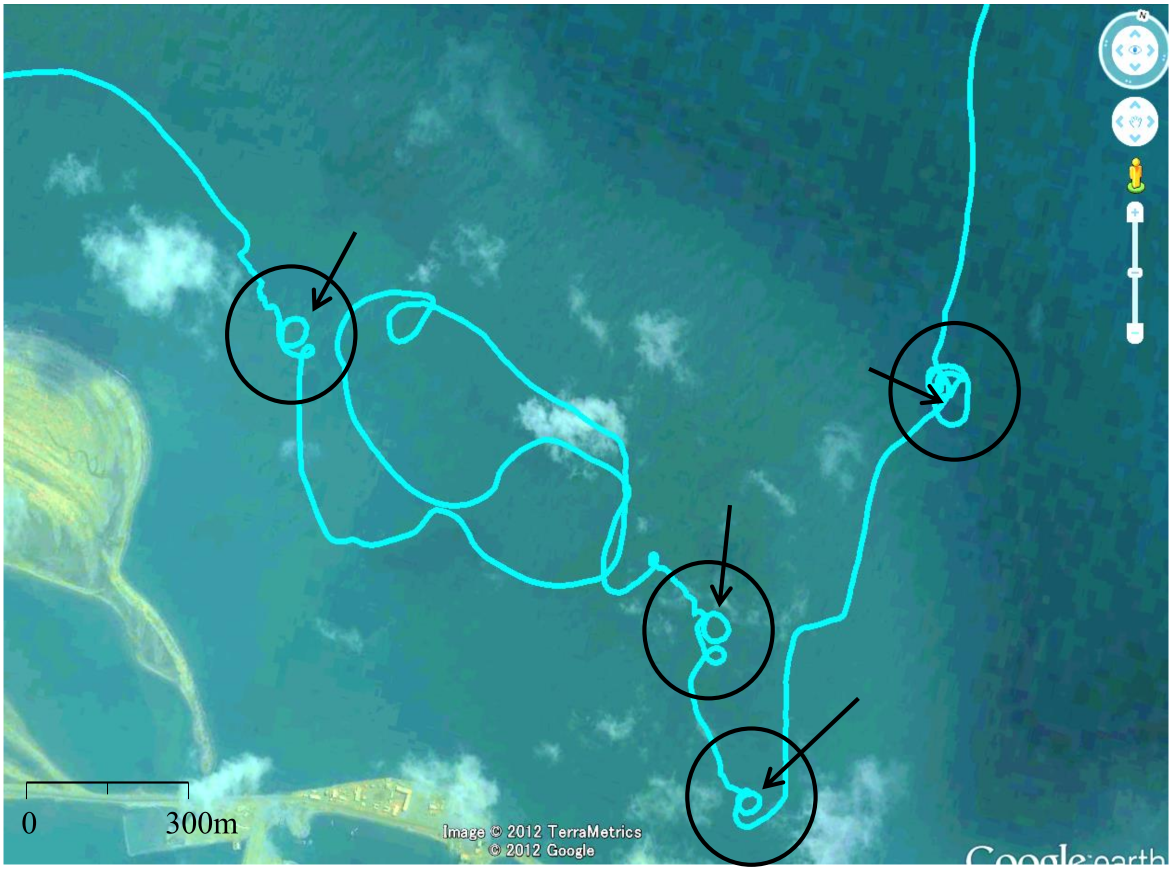


Figure 4.3. A route of a fishing trip with the locations of purse seine fishing hauls conducted during the trip superimposed on the google earth image (Map data: Google, GeoEye).

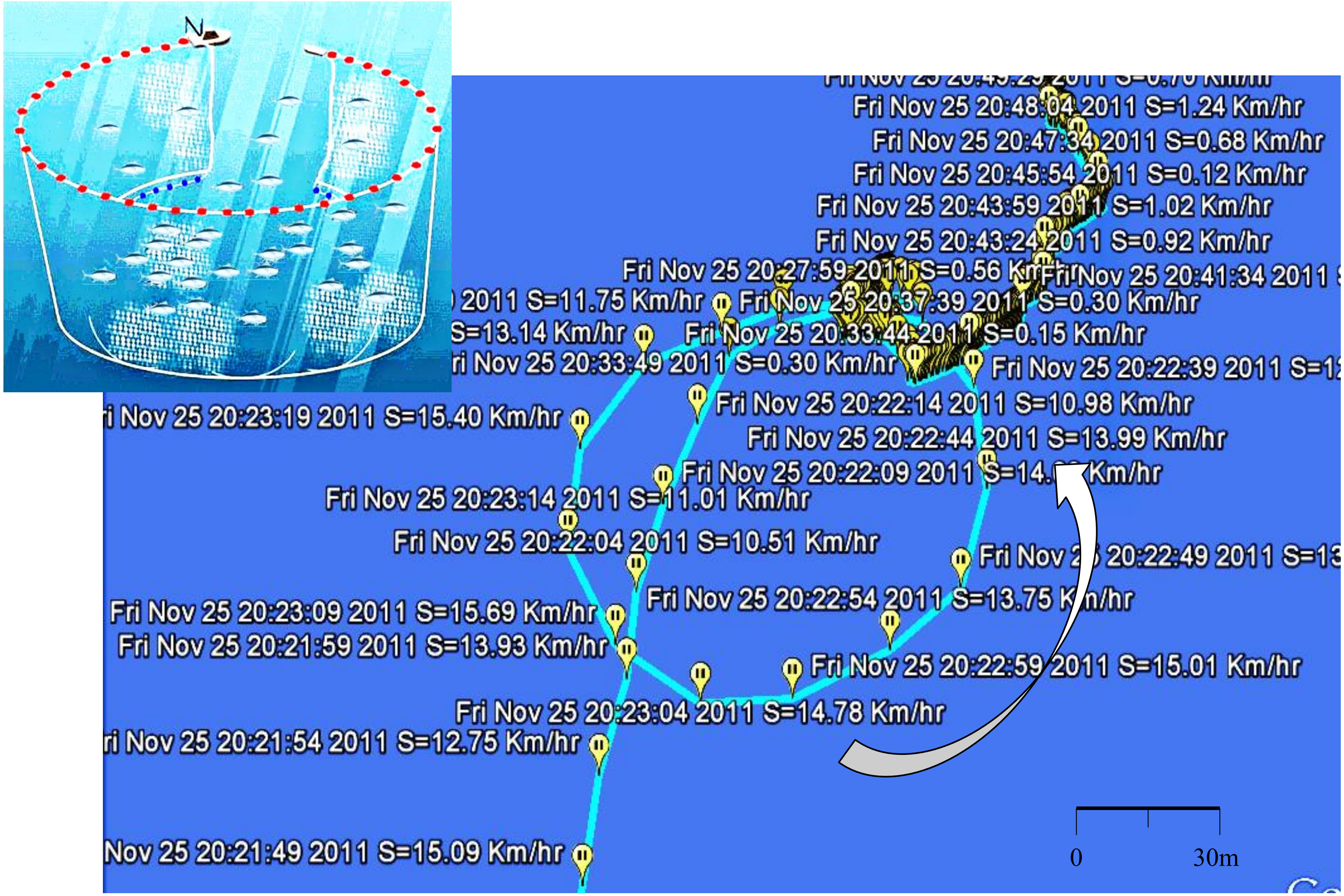


Figure 4.4. One of the purse seine fishing hauls and it shows clearly the hauling (encircling of fish school) and the usual low speed after hauling, which corresponds to the boat speed while drifting. A schematic diagram of purse seine is shown on the top left. (Map data: Google, GeoEye)

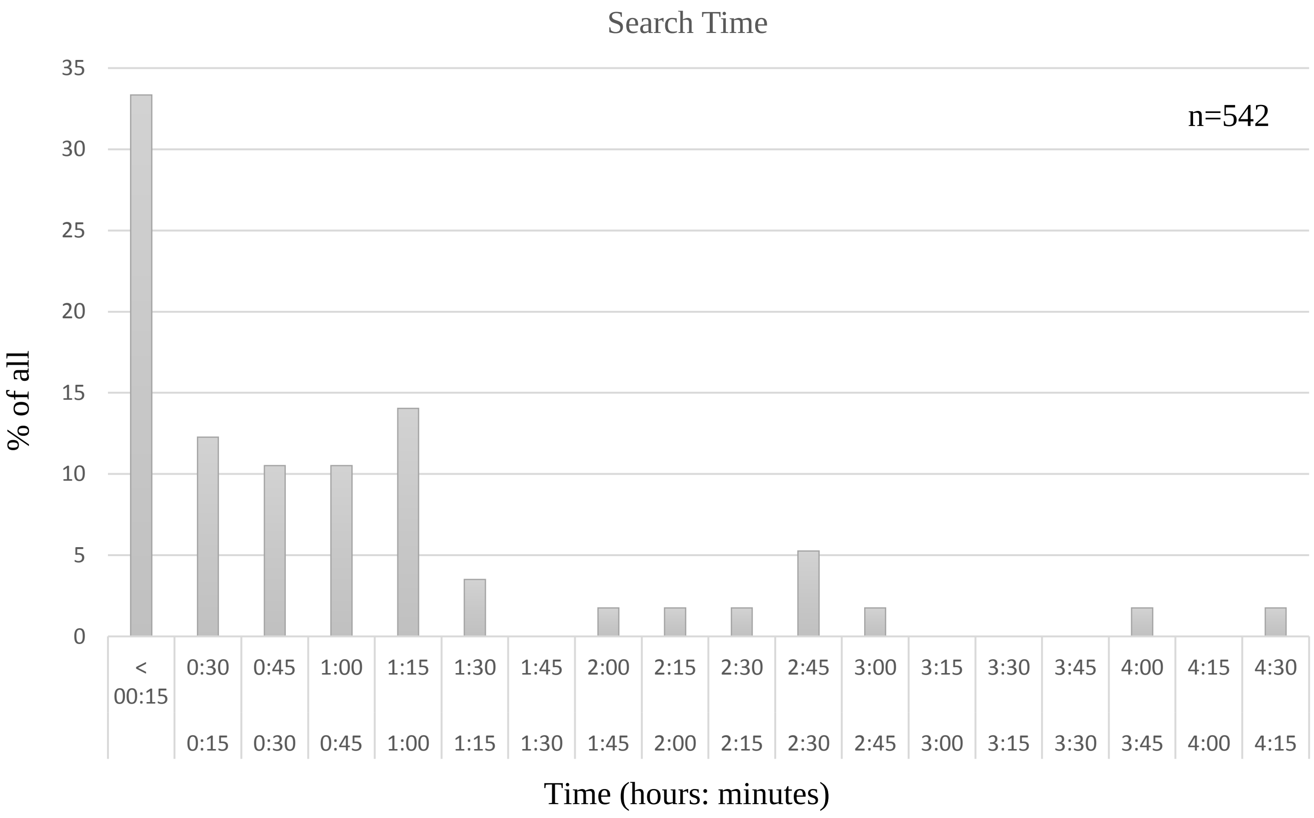


Figure 4.5. Frequency distribution of search time for Indian mackerel before every net deployment

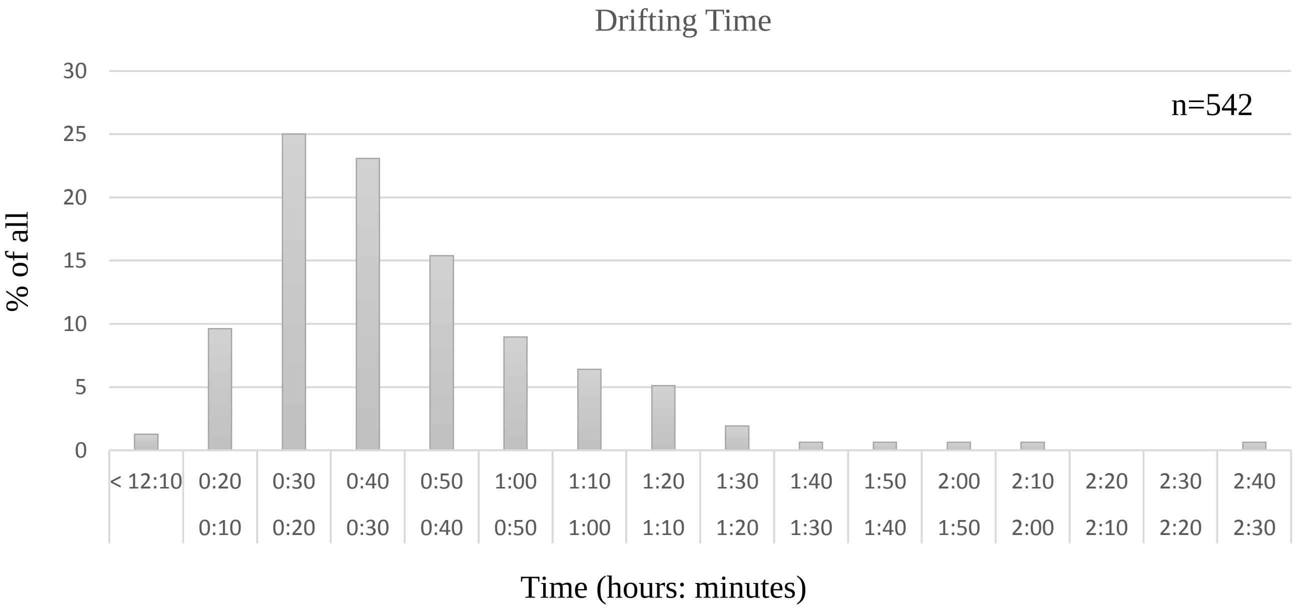


Figure 4.6. Frequency distribution of drifting time after net deployment and retrieval

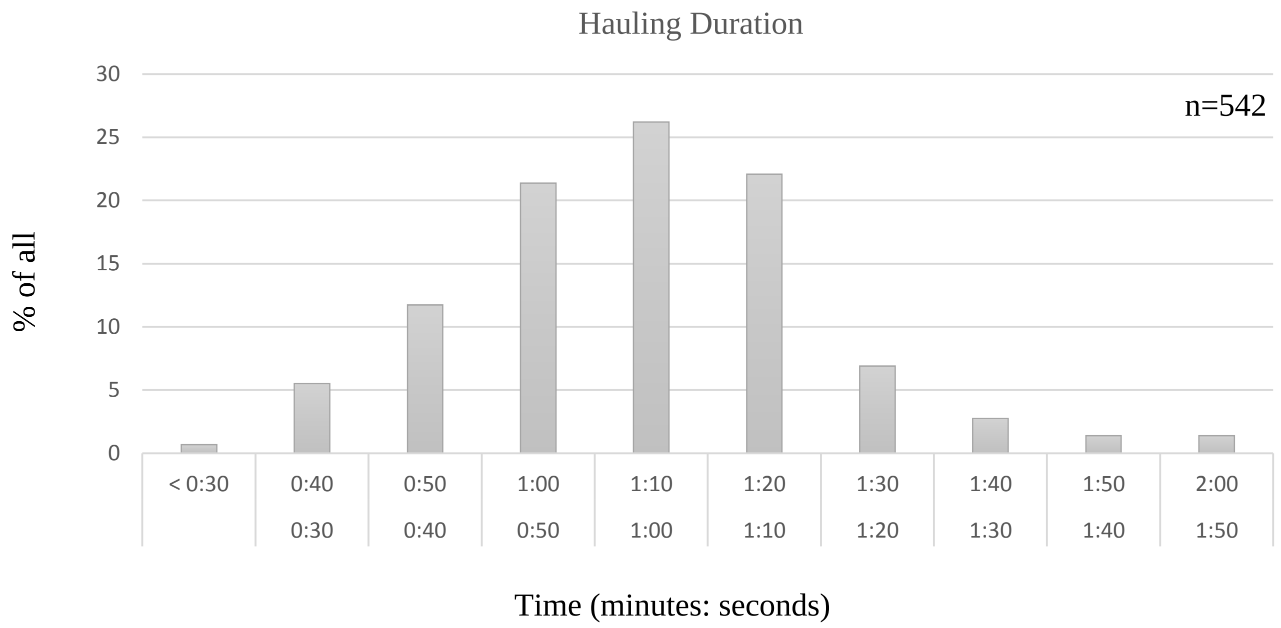


Figure 4.7. Frequency distribution of hauling durations of Indian mackerel purse seine net

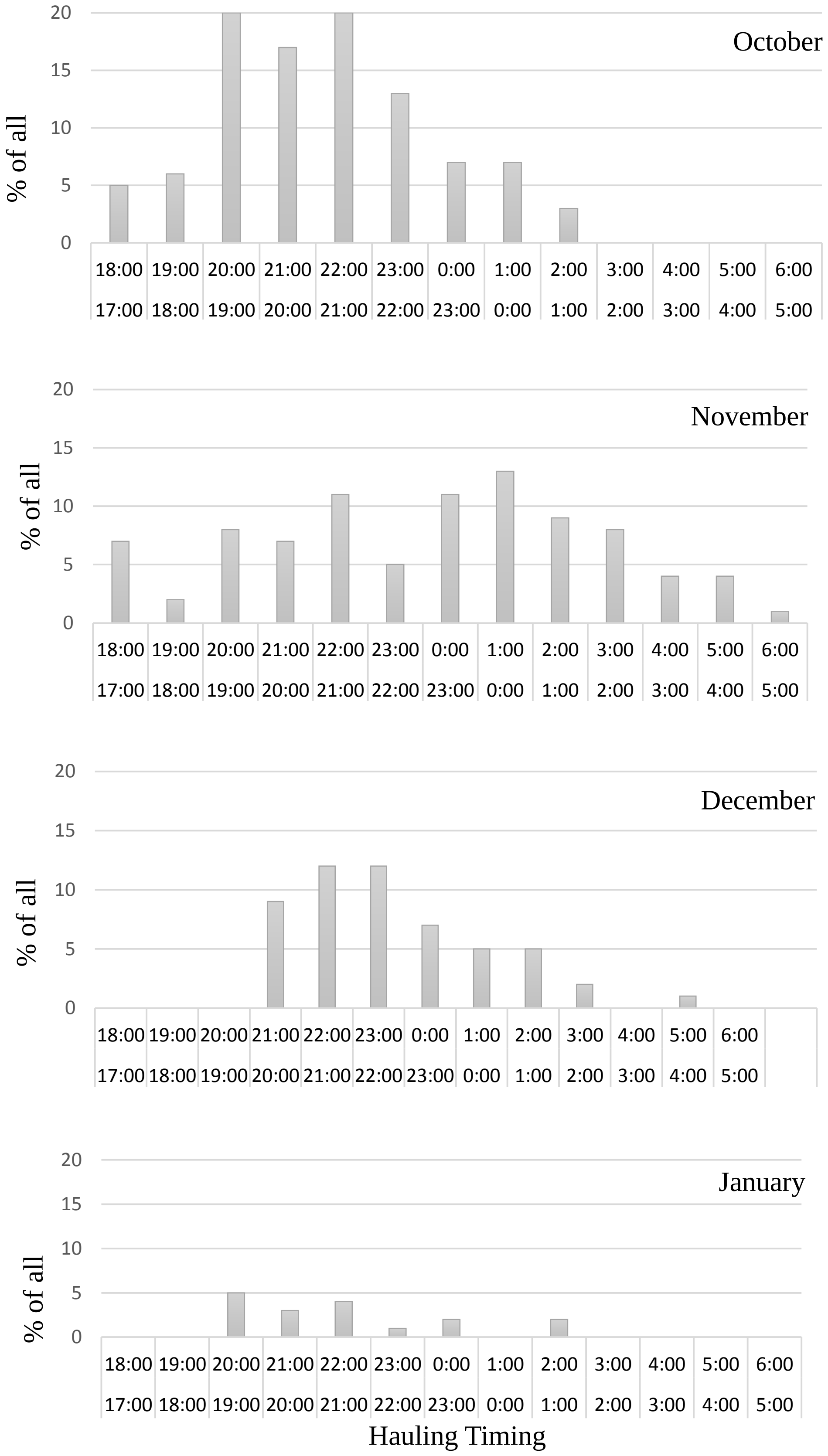
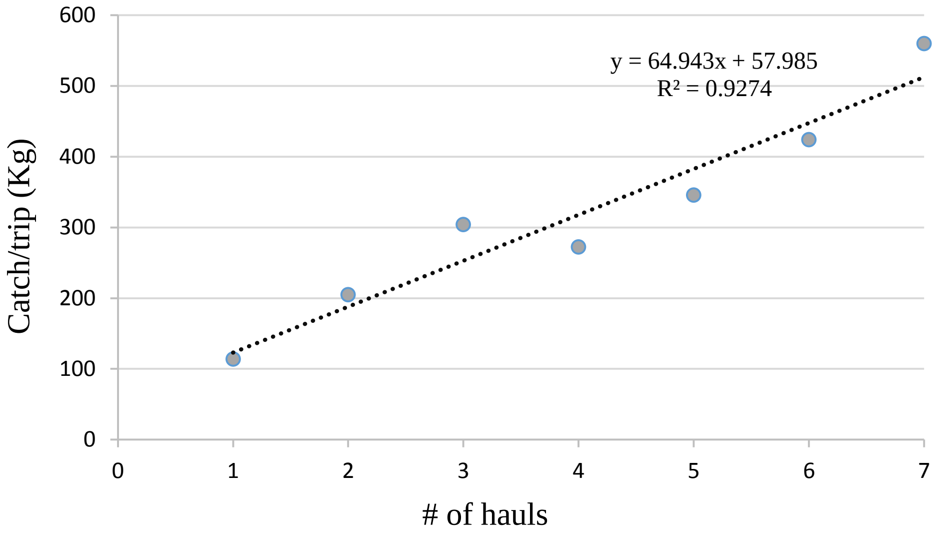


Figure 4.8. Frequency distribution of haul timing during the different months of the study period



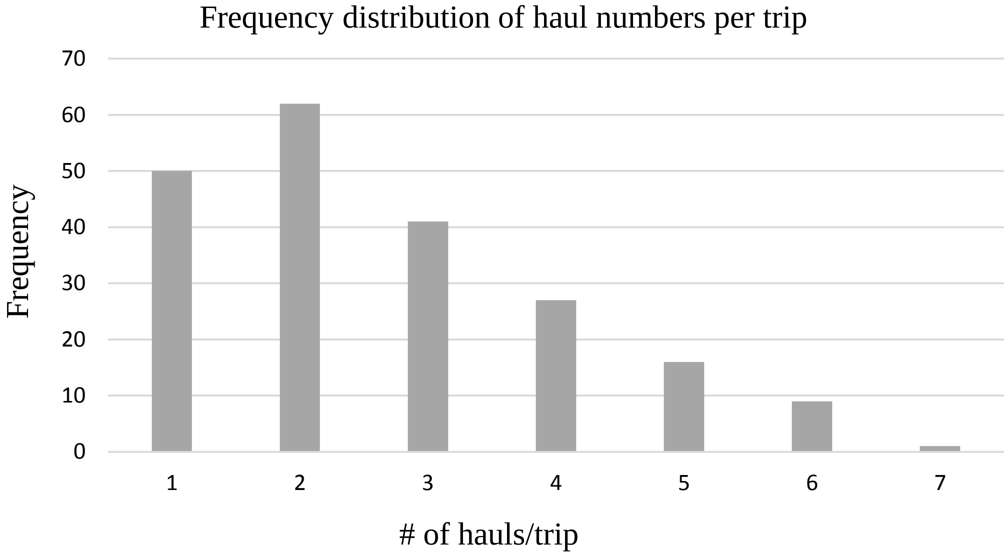


Figure 4.9. Number of hauls/trip plotted against the catch/trip (upper panel) and frequency distribution of haul numbers per trip (lower panel)

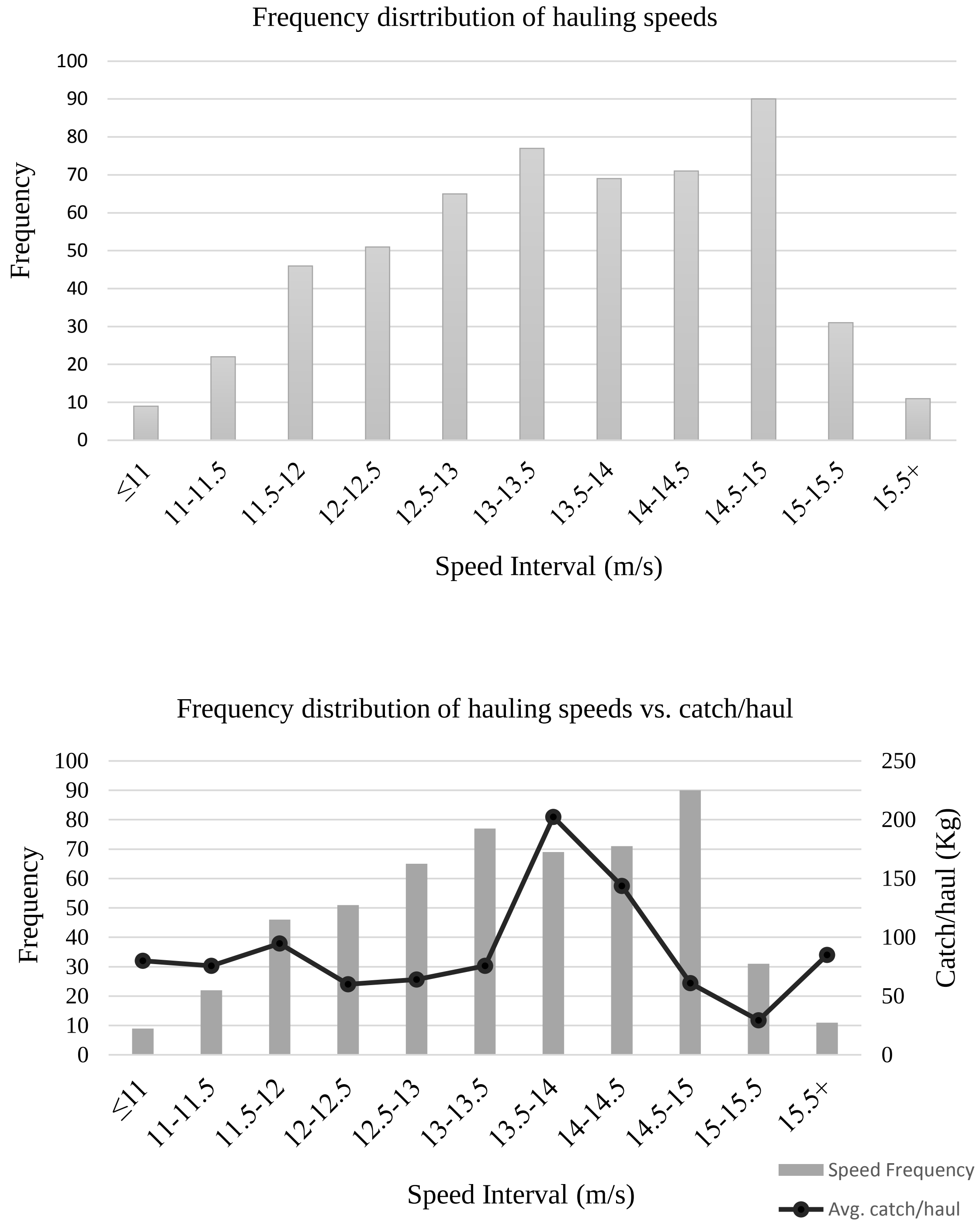


Figure 4.10. Frequency distribution of hauling speeds (upper panel) and catch/haul overlaid on the corresponding hauling speed (lower pane)

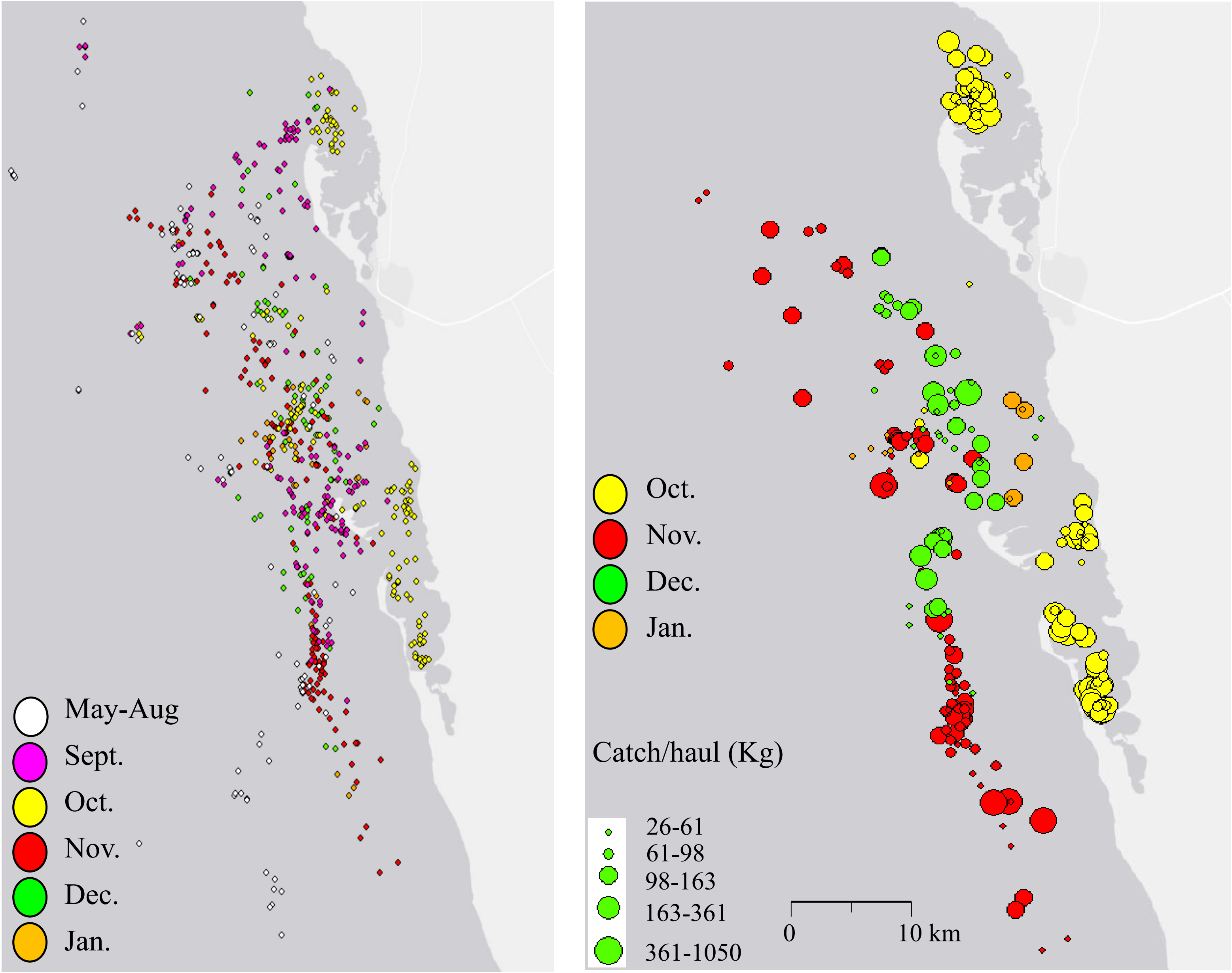


Figure 4.11. All fishing locations of Indian mackerel from May 2011 until January 2012 (left image) and Indian mackerel catch per haul distribution from October 2011 until January 2012 (right image)

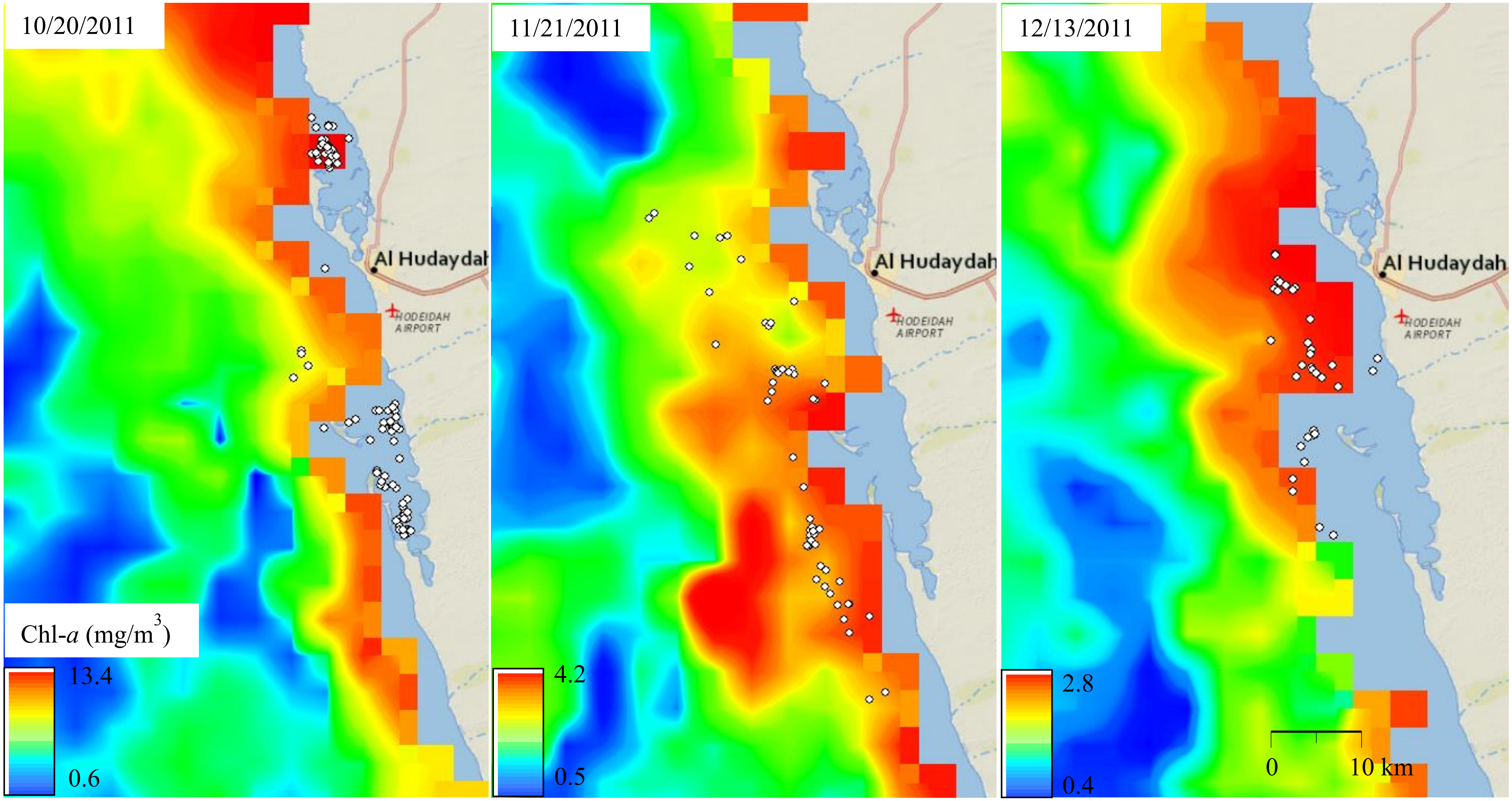


Figure 4.12. Indian mackerel fishing locations overlaid on weekly composites of Chl-*a* imagery and it shows the concentration of fishing locations in high chlorophyll waters. Fishing locations occurred inside semi-enclosed bays near the coast only in October (left image) where chlorophyll-*a* concentration was highest during the study period, which extends over 8 months from May 2011 until January 2012.

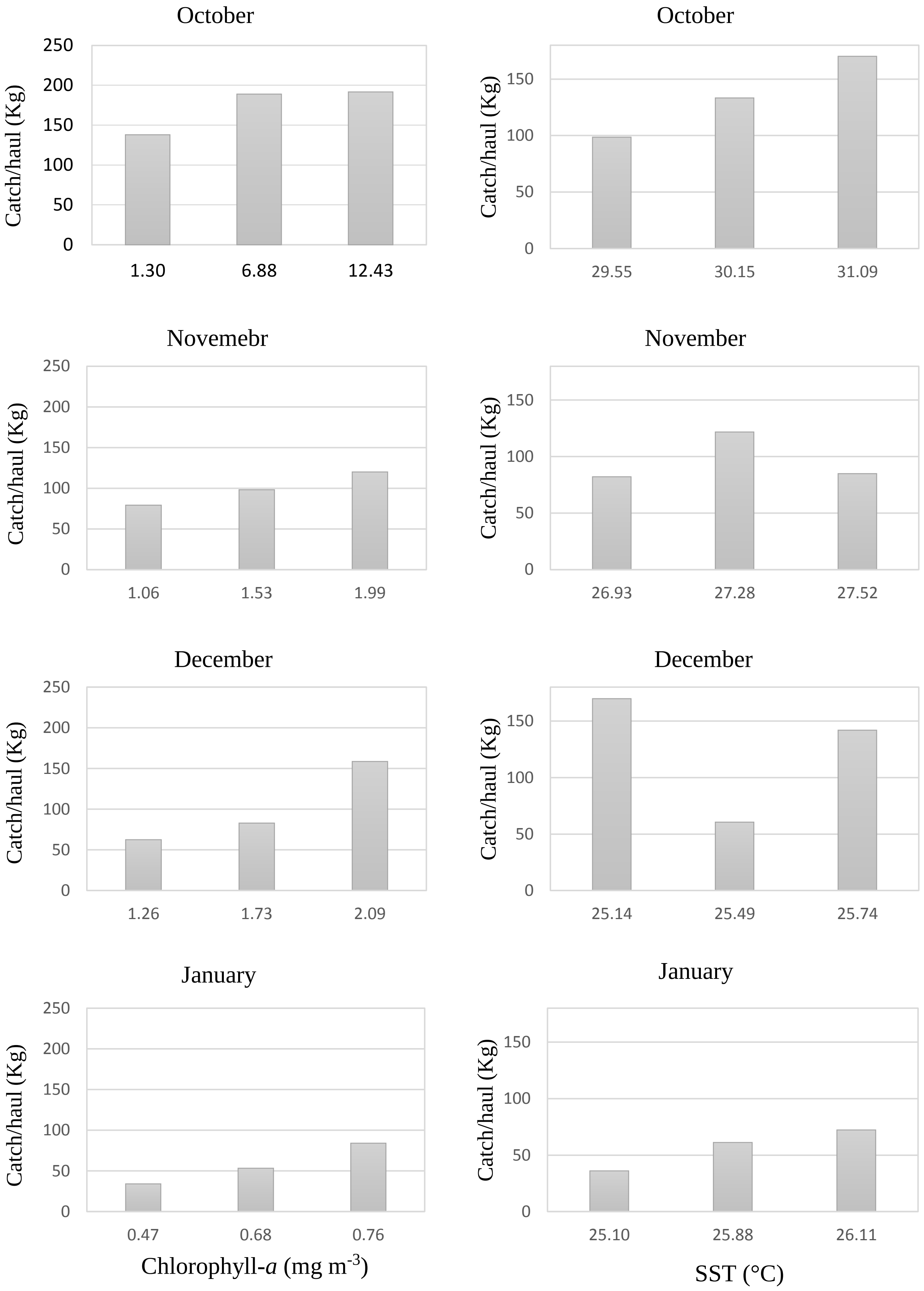


Figure 4.13. Catch per haul of high, mid and low averages of both chlorophyll and SST during the different months of the study period

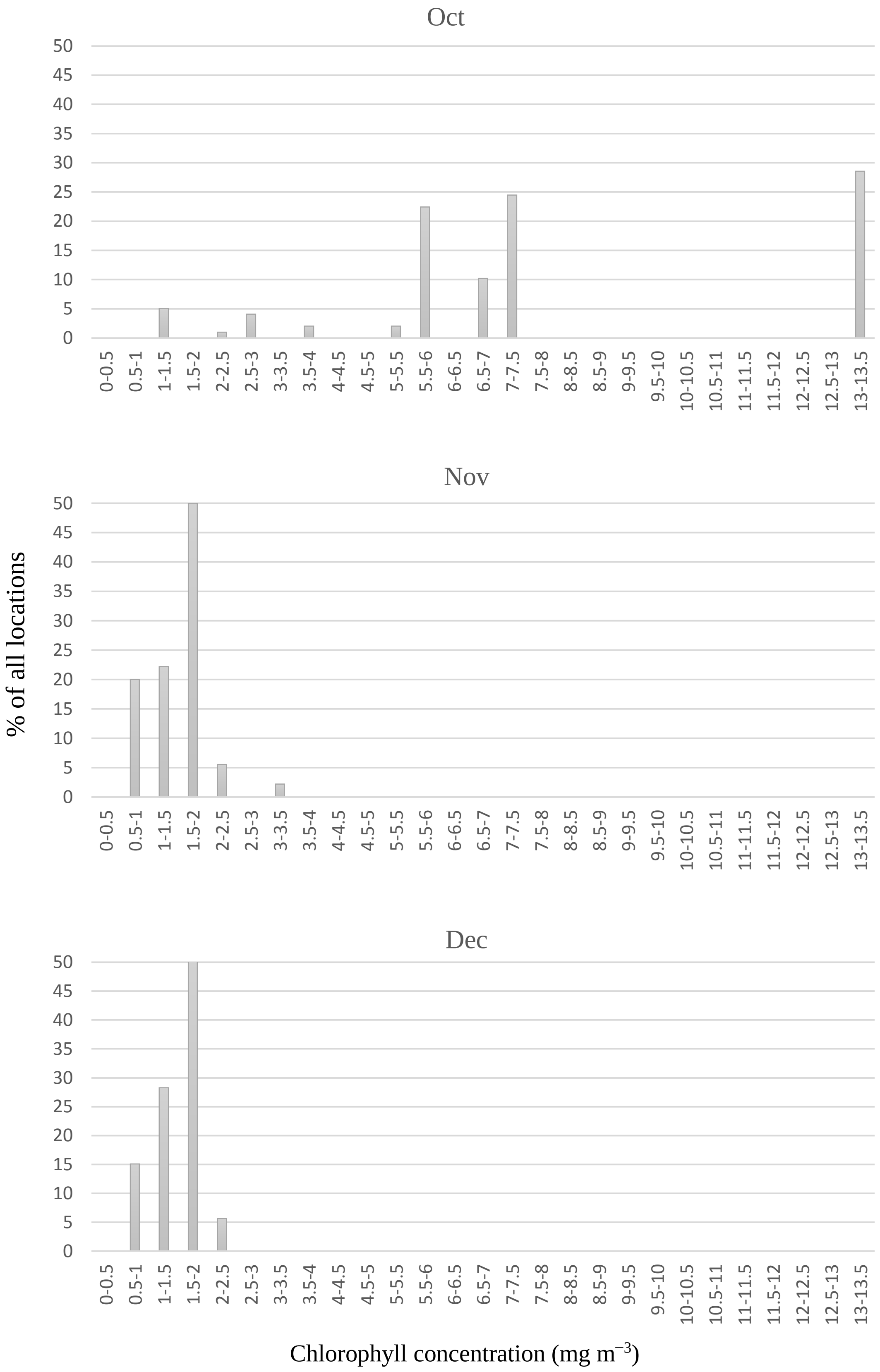


Figure 4.14. Frequency distribution of chlorophyll-*a* concentration at Indian mackerel hauling locations. Chlorophyll-*a* data is missing in summer months including September.

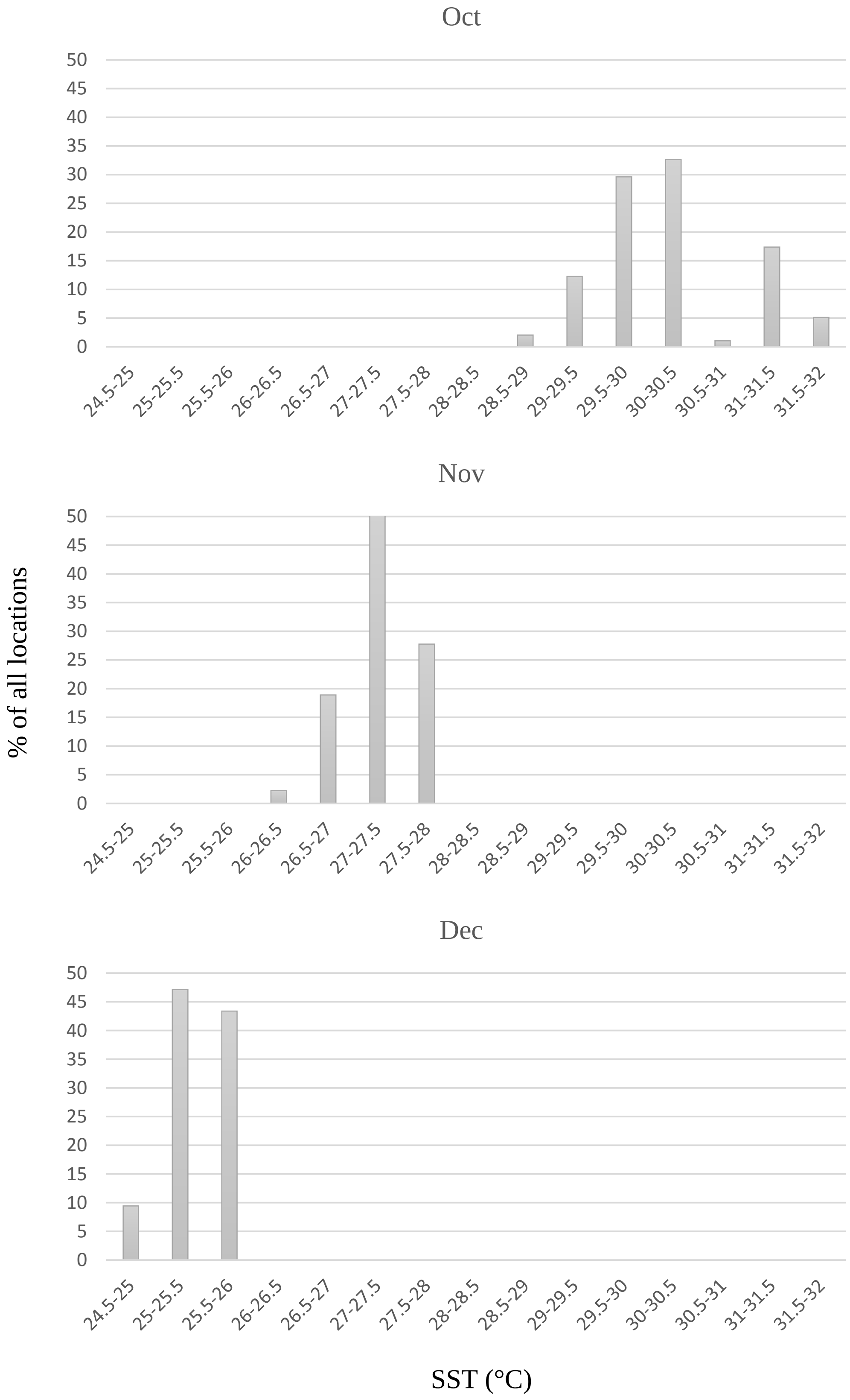


Figure 4.15. Frequency distribution of SST at Indian mackerel hauling locations

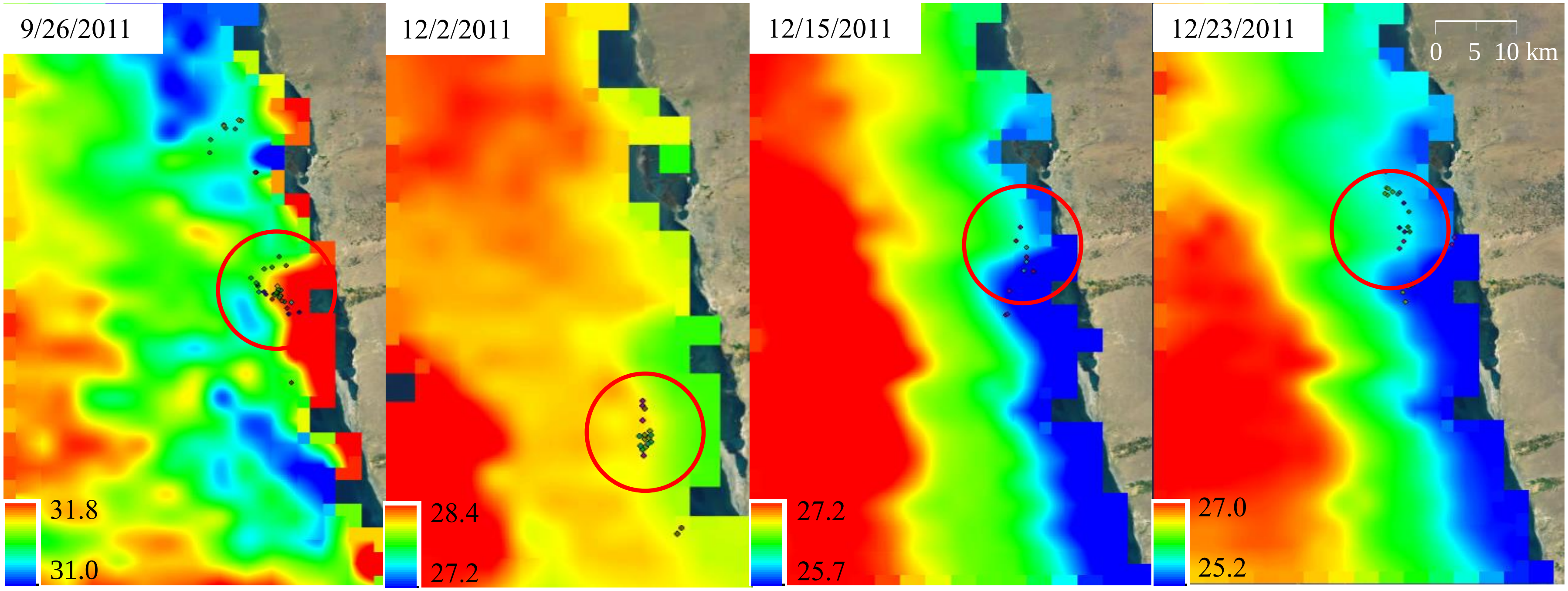


Figure 4.16. Indian mackerel fishing locations overlaid on daily SST imagery and it shows the concentration of fishing locations along SST fronts.

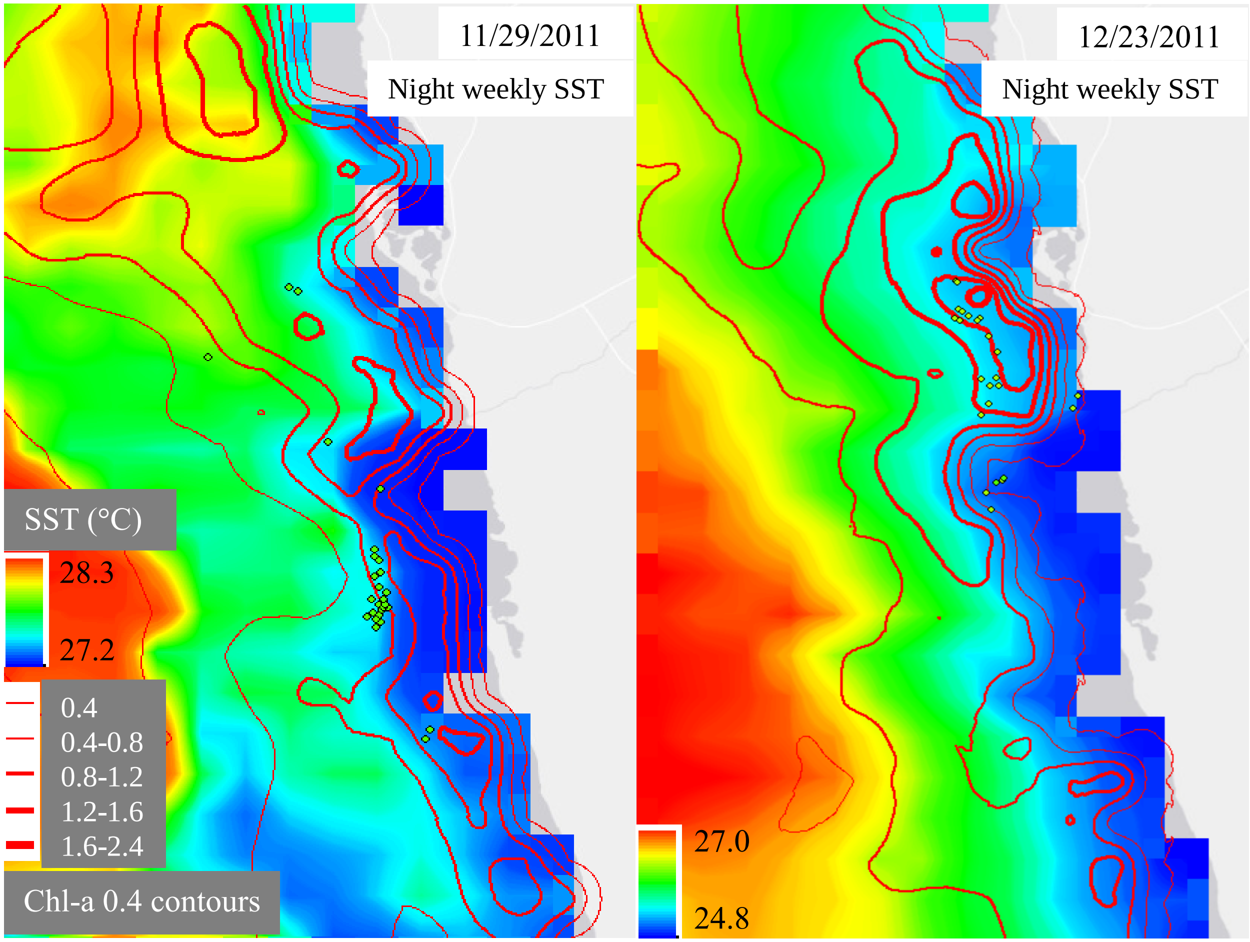


Figure 4.17. Indian mackerel hauling locations overlaid on SST imagery and 0.4 chlorophyll contours.

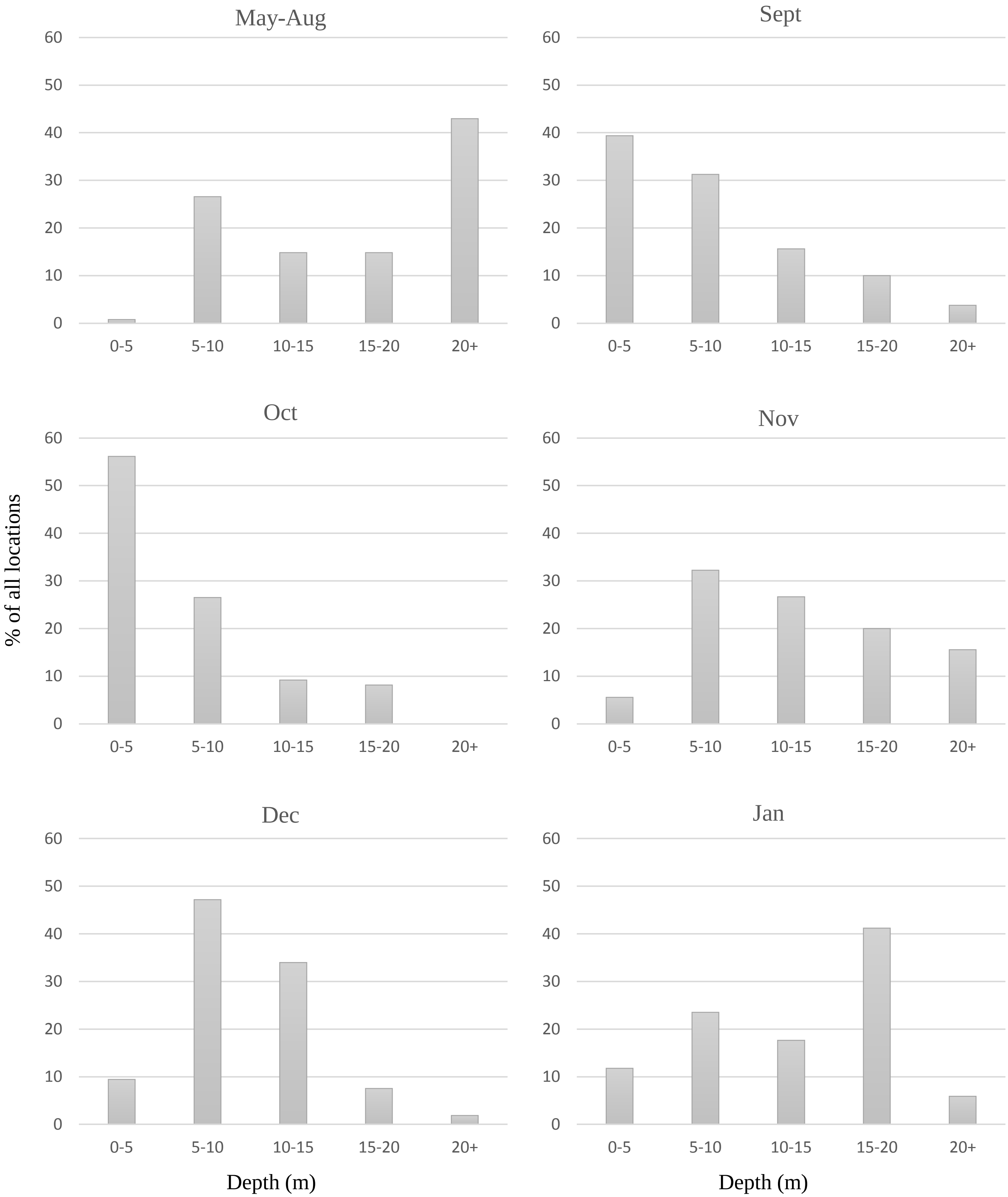


Figure 4.18. Frequency distribution of depths at Indian mackerel hauling locations

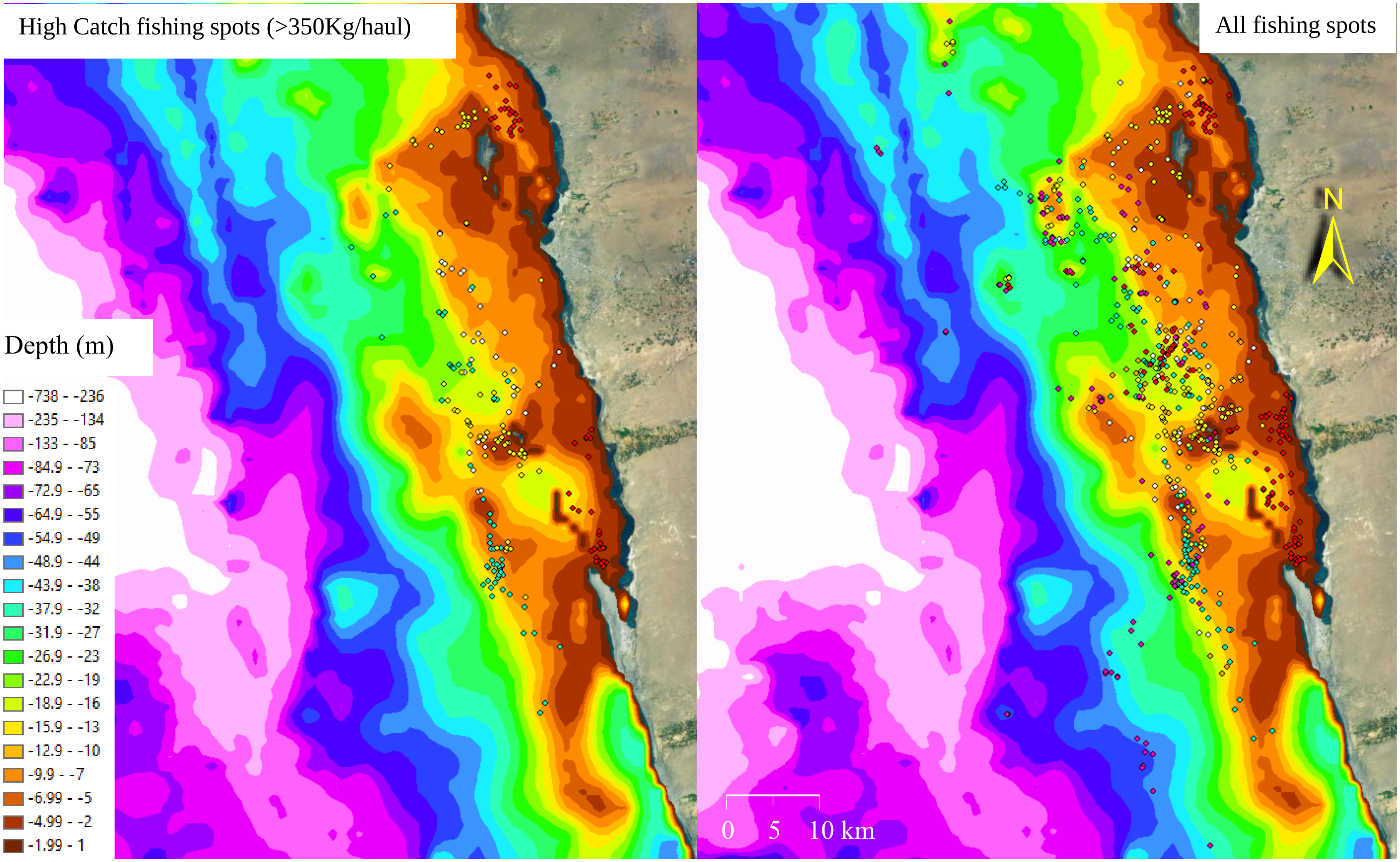


Figure 4.19. Indian mackerel fishing locations overlaid on bathymetric imagery and it shows that most of the catch come from shallow waters. The left image include high catch locations while the right image include all the fishing locations.

Table 4.1. $\text{CPUE}_{\text{trip}}$ and $\text{CPUE}_{\text{haul}}$ (standard deviation) and the corresponding number of hauls and number of days in different months. (Note: one trip= one night)

Month	$\text{CPUE}_{\text{trip}}$ (kg/trip)	$\text{CPUE}_{\text{haul}}$ (kg/haul)	# of hauls	# of days
Sept	230.4 (118.5)	125.7 (56.7)	177	88
Oct	235.0 (212.5)	95.9 (70.0)	142	66
Nov	193.4 (149.8)	69.2 (50.4)	144	48
Dec	226.8 (153.7)	106.3 (100.4)	87	33
Jan	126.0 (78.5)	76.8 (74.4)	28	11

CHAPTER 5

Pharaoh Cuttlefish Fisheries

5.1. INTRODUCTION

Rapid growth and short lifespan render cephalopod fisheries difficult to assess and manage (Pierce and Guerra, 1994; Payne *et al.,* 2006; Boyle and Rodhouse, 2008). Most cephalopod species targeted by fisheries are short-lived, usually with a 1-year life cycle and a semelparous life history strategy, with a single spawning soon followed by death (Boyle and Rodhouse, 2005). Individuals with a lifespan of 1 year do not survive until the fishing season in the following year. Even though abundance of cephalopods in the current year may be relatively high, stock size in the following year may be greatly varied due to high variability in their recruitments. Boyle and Rodhouse (2005) noted that the effect of environmental variables on abundance of annual species at multiple scales is the main reason for difficulties in establishing reliable stock assessment and management procedures.

While greater understanding of environmental influences on recruitment is frequently recommended for improved management of cuttlefish fisheries (Agnew *et al*., 2005; Boyle and Rodhouse, 2005), knowledge of the relationships between cuttlefish distribution and environmental variables has a potential to improve fisheries management (Ish *et al.,* 2004; Schön *et al.,* 2002). Understanding of environmental effects on population dynamics and species distributions of cephalopods could be used for their stock assessments to support fisheries management. Although environmental processes introduced into stock assessments generally include those that affect population dynamics of recruitment, however, their effects on spatial and temporal distributions and migration patterns of species are noticed by scientists only recently (Keyl and Wolff, 2008). Therefore, it is necessary to understand cuttlefish distribution and fishing activities for their sustainable use and management.

Commercial exploitation of *S. pharaonis* in the Gulf of Aden is centred off the south coast of Yemen. The cuttlefish fishery was commenced in 1966 and its virgin stock was large (Hariri *et al.*, 2000). Because of its high export value, assessment of the cuttlefish stock and estimation of potential yields have been attempted more or less continuously since the start of exploitation. Resource assessments have been based on catch and effort data, population dynamics modelling, trawl mesh selectivity trials and resource surveys conducted by fisheries research vessels and commercial trawlers. Damage to the spawning biomass during the 1970s and 1980s was caused by trawling operations of large stern foreign trawlers (Hariri *et al.,* 2000). Production of cuttlefish from both the Red Sea and Gulf of Aden waters of Yemen totalled 15,679 ton in 2012, 96% of which was made of *S. pharaonis*. The cuttlefish fishery is managed by closed seasons, which is regularly announced by the Ministry of Fish Wealth (MFW). However, fishers' compliance to the closure is low and enforcement of this management measure is weak (Alabsi and Komatsu, 2014).

This study aims to map spatio-temporal distributions of fishing grounds of pharaoh cuttlefish (*Sepia pharaonis*) and characterise the spatio-temporal distributions of catch per unit effort (CPUE). Next, the study aims to investigate environmental preferences of pharaoh cuttlefish from satellite data and implications of these results were discussed for the management of this species.

5.2. MATERIALS AND METHODS

5.2.1. Study area

The study was conducted offshore of Al-Luhaiyah (15°27'–16°07'N and 42°24'–43°50'E) in the southeastern Red Sea coast, 100 km north of Hodeida, the main city on the Red Sea coast of Yemen (Fig. 5.1). Fishing is the main livelihood activity of the coastal inhabitants of Al-Luhaiyah. Cuttlefish fishery and demersal fishery are the two principal fisheries of the area in addition to minor pelagic fisheries. Fishermen alternate between the two fisheries targeting cuttlefish during the two fishing seasons from February until May and from July until September and targeting demersal fish during the rest of the year.

5.2.2. Target species

Pharaoh cuttlefish (*Sepia pharaonis*) is one of the most economically important sepiid cuttlefishes. Geographical distribution of this species covers the West Pacific and the whole Indian Ocean extending to the Red Sea (Fig. 5.2). Pharaoh cuttlefish is a neritic demersal species occurring in coastal shallow waters down to a depth of 100 m (Chotiyaputta, 1995). Because of their benthic nature, they mostly feed on crustaceans like prawns and crabs, and small fish (Nair, 1993). Mean individual fecundity was 1,400 (800-2,700) eggs in the wild stocks (Chotiyaputta, 1982). Spawning occurs all year round with two peaks annually, as a consequence of the plasticity of their life cycle, which is less than 1 year either in the short or long mode (Nabhitabhata and Nilaphat, 1999).

In several species of Sepia (e.g. *S. officinalis*, *S. pharaonis*, *S. apama* and *S. dollfusi*), a range of developmental stages and egg sizes are found in the ovaries of sexually mature females during the spawning season, indicating that not all eggs mature simultaneously and that eggs are produced in multiple batches. The observations above-mentioned suggest an intermittent terminal spawning strategy in these species (Boletzky, 1987a; Gabr *et al.*, 1998; Hall and Fowler, 2003).

5.2.3. Description of cooperative research

Cooperative research with small-scale fishermen engaged in *S. pharaonis* fishery was conducted to characterize the fine-scale, spatio-temporal characteristics of fishing activities and fishermen’s behavior in Al-Luhaiyah. Fishermen were asked to deploy portable GPS data loggers to record fine-scale movement patterns of fishing boats, of which a mean overall length was 7 m, from fishing trips for *S. pharaonis* in the period from June 2012 up to September 2013.

5.2.4. Data loggers

Two types of data loggers, 23 loggers of i-gotU USB GPS Logger - GT-600 and 17 loggers of VuPoint GPS Logger GPS-MA200-VP (Fig. 5.3). They were small and easy to use, and had big battery capacity more than 10 days with data recorded at 1-minute intervals during 12 hours operation per day. They were ideal for the short trips of cuttlefish fishery. Internal 64 Mb storage capacity was adequate for recording approximately 262,000 waypoints. Software called “@trip PC” working on Windows PCs was used to configure the loggers, download the data and visualize trip routes before processing. The GPS loggers create two data files for each trip: csv and gpx files containing the recorded data and trip waypoints with routes, respectively. The loggers were set to record the data for 12 hours from 6:00 a.m to 6:00 p.m because fishing always occurred only during the daytime. The loggers were set to turn on and off automatically according to preprogrammed time. This function of the loggers was very convenient because fishermen didn’t need to do anything except carrying the GPS logger onboard the fishing boat while in a trip. The loggers had a built-in rechargeable 750mAh lithium-ion battery that could be used for 10 days (in case of recording interval of 1 minute) without recharge. The data were downloaded to a PC once a week.

5.2.5. Data collection

The GPS loggers were given to the fishermen in the morning before their departure and retrieved upon their return from the sea to the landing site. Between 20 and 30 GPS loggers were simultaneously used for the study period according to availability of fishermen to voluntarily participate in the study. During the first six months from May to November 2012, half of GPS loggers were used because the rest were used in another study on pelagic fishery. From December 2012 to September 2013, all the GPS loggers were used for the study on the cuttlefish fishery. A co-worker collected the loggers after every trip and collected catch data of cuttlefish at the landing site. Later, the catch data were compiled and the GPS data were downloaded from the GPS loggers to a PC once a week.

5.2.6. Data Types

5.2.6.1. Fishing data

GPS logger data

Data on fishing boat positions collected by using a GPS logger provided location (latitude and longitude), vessel speed in km/h, date and time.

Catch characteristics

Catch data on each trip was collected at the landing site including catch in weight (kg/trip) and crew number. There were no bycatch or negligible quantity of bycatch in cuttlefish fishery.

Boat and fishing gear characteristics

Data related to fishing boats for the cuttlefish fishery were collected one time during the study period and consisted of name of the owner, boat type and overall boat length (m). The fishing gear used to capture cuttlefish was only hook and line (called jigging). Artificial lures (artificial baits) of size 3.0 were used for fishing. One artificial lure was usually used in one line.

5.2.6.2. Remote sensing data

Sea surface temperature (SST) and bathymetric data were downloaded via the internet with ArcGIS function and analyzed as environmental data. Other environmental data, such as chlorophyll-*a*, wind data, currents data and sea surface height anomaly (SSHA) were not available for the study area. Only composites of SST data were used because it minimized missing data in daily SST images that had not covered all the study area due to clouds.

5.2.7. Data analysis

Temporal resolution of catch data of cuttlefish fishery was one trip, which varied from one day to three days. A typical single one-day trip was 6 h in average corresponding to ~360 locations because boat positions are recorded at one-minute intervals. It was necessary to find the most appropriate approach to distribute the total catch of one trip among fishing locations estimated from fishing boat positions. If cuttlefish catch of one trip by one boat was well correlated with some indicator of fishing effort, then we could use fishing effort to distribute the total catch among fishing locations. According to inquiry to fishermen, they continued fishing at the same location during good catch, and shift to a new location when the catch became small or none. Based on this information, data analysis was conducted as mentioned below.

5.2.8. Initial data processing

Each trip allocated a code had GPS data (location, time, distance, etc.) and catch data (catch, no. of fishermen and fisher’s name), which were combined with a corresponding GPS file. The files were imported into a geodatabase and then into the ArcGIS platform (ArcGIS 10.0) for subsequent processing.

Exclusion of non-fishing data from position data

GPS data of one trip obtained by a GPS logger included not only fishing data but also non-fishing data such as traveling, anchoring, landing on the islands or on land. Geoprocessing tools were used to exclude the non-fishing position data.

The fishermen indicated that they didn’t fish in waters just close to the islands. Since GPS-derived speed data of a fishing boat near the island was always zero during early time in the day and late in the day, it indicated that the fishing boat was anchored there before started fishing or after returned from the sea to the island to have a rest on land or to spend the night. Therefore, GPS data near the islands were non-fishing data and hence excluded from the data by creating a buffer zone to mask the islands and a distance of 50 m from their coasts.

It was necessary to remove traveling data and translocation data (shifting between two fishing grounds) from the recorded GPS data. Fishing for cuttlefish was conducted during boat drifting. Although boat speed is influenced by wind speed, traveling speed of the boat is much higher than that of drifting. In order to decide a threshold for the boat speed while not fishing, the speed data during drifting were examined. Although most of the speeds during drifting ranged between 0 and 3 m s^{-1}, those during traveling or shifting from one area to another were more than 10 m s^{-1}. Therefore, a threshold of fishing speed was decided to be less than 3 m s^{-1}. Data points with speeds less than 3 m s^{-1} were filtered from the GPS data and regarded as fishing locations in this study.

The whole dataset of fishing positions of all trips was created and imported from excel files into ArcGIS platform through geodatabase and subsetted into monthly datasets to be able to analyse the data on a monthly basis.

Calculation of CPUE

Two indices of fishing effort could be identified from time and location data. One was time spent in a fishing ground and the other was distance moved between two successive fishing locations. Fishermen indicated that in most cases they fished in a single fishing ground in any single trip. This trend of staying in the same location was also clear from the data when boat positions were visualized. Therefore, one trip has generally one representative fishing ground and almost all the data points were aggregated around this fishing ground. The total duration of fishing activities, namely total effort, was obtained by summing fishing activity time. By dividing the total catch by the total time of fishing activity, catch of one minute fishing activity per boat (catch per unit time per boat) was calculated.

In order to examine the relationship between catch and effort, the study area was divided into polygons of 2.25 km^2 (1.5×1.5 km). The total catch (kilograms) and total effort (hours) of each polygon are accumulated from all boats' positions located in this polygon during the whole month. Finally, each polygon, which was regarded as a fishing ground, had accumulated total catch and total hours per month.

Monthly catch per unit effort for the whole cuttlefish fishery (from all boats and from all polygons) was obtained from the monthly whole catch in kilograms and the monthly whole effort as time spent fishing by 25 fishing boats that supplied GPS and catch data to this study. The effort in hours was converted to days fished by dividing the total hours by 6 (average fishing time of a fishing day).

In order to calculate monthly catch per unit effort for each polygon ($CPUE_{polygon}$), the total catch from all boats was divided by the total time spent in that polygon during a specific month. This step was repeated for the dataset of every month from August 2012 to September 2013. The results were visualized by ArcGIS with colours according to standardized ranges of CPUE for all fishing months. Seasonal CPUE of each polygon was also calculated from seasonal accumulated catch and fishing days of spring from March to May, summer from June to August, autumn from September to November and winter from December to February. Monthly and seasonal fishing efforts of each polygon ($\mathrm{EFFORT}_{\mathrm{polygon}}$) were also visualized as those of CPUE of each polygon.

Fishing grounds distribution and environmental conditions

Distributions of CPUE of *S. pharaonis* during the whole study period from August 2012 to September 2013 were overlaid on bathymetric maps. Fishing locations were also superimposed on 8-day SST images for analysis on relation between environmental variables and fishing grounds formation. Frequency distribution of depths at the fishing locations was prepared to investigate their range in the fishing grounds and the optimal range in different months during the study period.

5.3. RESULTS

5.3.1. Effort and catch relationship

Effort-catch relationship (Fig. 5.4) indicated that fishermen wisely selected fishing grounds because fishermen invested more time on fishing grounds which yielded more catch and shifted shortly from the fishing grounds when were not productive. The relation also indicated that the time was an accurate index of the effort and appropriate to be used in the calculation of CPUE.

5.3.2. Catch per unit effort for the whole fishery ($\mathrm{CPUE_{whole}}$)

$\mathrm{CPUE_{whole}}$ of the monthly whole fishery ranged from 19.2±5.2 to 51.3±12.3 kg boat^{-1} d^{-1} (Fig. 5.5). It was higher in March (49.4 kg boat^{-1} d^{-1}), April (51.3 kg boat^{-1} d^{-1}) and August (49.7 kg boat^{-1} d^{-1}) in 2013 and was lower in November (14 kg boat^{-1} d^{-1}) and October (19.2 kg boat^{-1} d^{-1}) in 2012. CPUEs were significantly lower in 2012 than in 2013. CPUEs in August of 2012 and 2013 valued 21.2±4.3 and 49.7±17.9 kg boat^{-1} d^{-1}, respectively and those in September of 2012 and 2013 valued 21.2±7.7 and 41.9±9.9 kg boat^{-1} d^{-1}, respectively.

5.3.3. Spatio-temporal distribution of $\mathrm{CPUE_{polygon}}$

Heterogeneity of site-specific $\mathrm{CPUE_{polygon}}$ was observed among different fishing grounds. CPUEs ($\mathrm{CPUE_{polygon}}$) ranged from 17 to 204 (±15.2) kg boat^{-1} d^{-1} in February 2013 and from 13 to 164 (±22.1) kg boat^{-1} d^{-1} in July 2013. $\mathrm{CPUE_{polygon}}$ was significantly lower in 2012 than in 2013. Spatial heterogeneities of site-specific $\mathrm{Effort_{polygon}}$ and $\mathrm{CPUE_{polygon}}$ for different months and seasons were shown in Figs. 5.6 to 5.11. Monthly frequency distributions of $\mathrm{CPUE}_{\mathrm{polygon}}$ from January to September of 2013 (Fig. 5.12) and from August to October of 2012 (Fig. 5.13) showed that the $\mathrm{CPUE}_{\mathrm{polygon}}$ was higher in March to April and in August. $\mathrm{CPUE}_{\mathrm{polygon}}$ for the whole study period indicated that CPUEs were between 20 and 50 kg boat^{-1} d^{-1} at most of the polygons (Fig. 5.14).

5.3.4. Spatial dynamics of fishing grounds

Monthly total number of fishing grounds (represented by polygons) was the highest (232 polygon) in February and was high in March, May and July (167, 172 and 154, respectively) in 2013 (Fig. 5.15). Yearly total number of fishing grounds (polygons) was 375. Most of fishing grounds (122 polygons) were visited as a fishing ground by fishermen only at one month of a year and 87 polygons were visited twice or three months a year. Fishing grounds visited most frequently in 10, 11 and 12 months a year amounted 14, 14 and 6 polygons, respectively (Fig. 5.16).

5.3.5. Pharaoh cuttlefish distribution and environmental conditions

This species occupied shallow bottom depths within 20 m (88.9% of fishing locations) and an average bottom depth was 12.4±9.8 m. Frequency distribution of bottom depths at the fishing locations is shown in Fig. 5.17. This tendency was shown with monthly $\mathrm{CPUE}_{\mathrm{polygon}}$ from January to September 2013 on a bathymetric map (Fig. 5.18). Fishing locations of *S. pharaonis* superimposed on 8-day composites of satellite SST images (Fig. 5.19 and 5.20) showed fishing locations appeared to occur at higher SSTs, but SSTs are usually affected by the bottom depth.

5.4. DISCUSSION

5.4.1. Distribution of fishing grounds and environmental variables

The distribution of monthly CPUEs in regards to bathymetry indicated that the CPUEs were clearly concentrated at shallow bottom depths in March/April and in August/September periods. Thus, fishing grounds are distributed in shallow bottom depths less than 20 m. This genus (*Sepia*) usually spawns in shallow inshore waters (Rodhouse *et al.,* 2014). Fishermen indicated that this species spawns twice a year: once from late-winter to early spring and once in late summer according to inquiry conducted along with this study. They reported morphological differences between fished individuals from these two periods. Two spawning seasons, in spring and in summer, were reported for this species from the Gulf of Aden by Sanders (1981) and Aoyama (1989). Combining this information with the high CPUE associated with shallow bottom depths occupied in two seasons suggests two cohorts of this species aggregate for spawning in shallow bottom depths twice a year. The fishermen also reported that cuttlefish usually spawned in sponge habitats on which their eggs were hanged and which was suitable for egg deposition. The two aggregation sites suggest protected areas for spawning. Cuttlefish (Sepiida) are characterized by offshore feeding grounds separated from the inshore spawning grounds. Their ontogenetic migrations are quite short (tens to low hundreds of kilometres) but could result in a strong seasonal variability in abundance especially in their localized spawning grounds (Rodhouse *et al.*, 2014). The winter and summer aggregation sites may be located around shallow islands in the north and in the area between the mainland and Humar and Bawared offshore islands, respectively. These locations may provide not only sponges as spawning substrates but also nursery areas. The whole geographic distribution of this species, mainly in shallow bottom depths less than 25 m near the coast, suggests small home range and minimal migration between spawning, nursery and feeding grounds.

The aggregation of cuttlefish in a small spatial range during spawning leads fishermen to easily target them. It is possible that fishing disturbs the spawning activity and adversely affects the recruitment success, and eventually causes a serial depletion of populations. For rational management of the cuttlefish fishery, authorities should consider to establish a spatio-temporal closure of fishing activity of this species during the spawning time to protect the spawning aggregations and improve the recruitment potential. It is especially important to place a complete ban on bottom trawling, in areas less than 25 m deep, for protecting sponge habitats as spawning grounds of this species.

5.4.2. CPUE as an index of abundance

Effort in hours fished (Fig. 5.4) per month explains accurately monthly catch fluctuation. The relationship is exclusive for the specific month (duration). Effort in hours fished explained 99% of the variability in catch. Therefore, effort in hours was used to allocate the total catch among different locations.

For rational management of this species, it is advisable to conduct observation of the CPUE of this species during the fishing seasons to monitor tendency of increase or decrease in abundance. For this purpose, the method developed in this study is very practical because CPUE of small-scale fishery can be estimated from only landings and GPS data of fishing boats. According to the in-season assessment, the fisheries authorities can decide the optimal time to close the fishery to ensure percentage escapement (e.g., 40% of the pre-season stock) of the stock to contribute to spawning when a certain percentage of the stock has been fished.

5.4.3. Fluctuations in abundance

5.4.3.1. Attributed to environmental variability

The significant difference in CPUE between 2012 and 2013 suggests a high fluctuation in abundance of this species which is not attributed to exploitation, but otherwise can be attributed to environmental variability, e.g., recruitment success. Recruitment success is affected by the environmental factors around the spawning time (Wang *et al.*, 2003). They influence survival rates at different development levels through its effect on processes such as hatching rate, growth rate and transport to suitable nursery grounds (Rodhouse *et al.*, 2014). For example, high temperatures within the optimum range after relase of eggs will shorten the time to hatch and increase growth rate, and eventually minimize mortality at critical stages resulting in high survival rates. Thus, it is reasonable that spawning grounds are formed in shallow bottom depths where water temperature is higher than in deeper bottom depths. Availability of food source and transport to suitable nursery areas also affect survival rates. In this connection, foods for juveniles may be abundant in sponge habitats as spawning grounds.

Most of the variability in cuttlefish stock biomass is thought to be related to environmental variability. Hence, observation of environmental variables around the spawning time will help us to understand future fluctuations in cuttlefish abundance and this will contribute to improved management of this fishery.

5.4.3.2. Attributed to change in exploitation level

Another possibility for the high CPUE in 2013 can be attributed to the high spawning stock biomass of *S. pharaonis* at an earlier spawning time, probably in 2011 or 2012. Investigation of exploitation level of cuttlefish during the last four years between 2010 and 2013 has indicated a relaxation in fishing level in 2011-2012. The so-known crisis of 2011, synchronized with the Arab spring, resulted in severe shortage in fuel supply and sharp increase in fuel prices all over the country and caused the fishing activity to stop during most of the year in 2011-2012. Therefore, high spawning stock biomass in 2011-2012 probably affects cohort strength and result in abundance increase of next generation. Therefore, the increase in CPUE, which started to be noticed in the winter in 2013, and continued until the second fishing season in summer, may be attributed to the high spawning stock biomass in 2011-2012. In this way, annual species may respond to exploitation level very quickly.

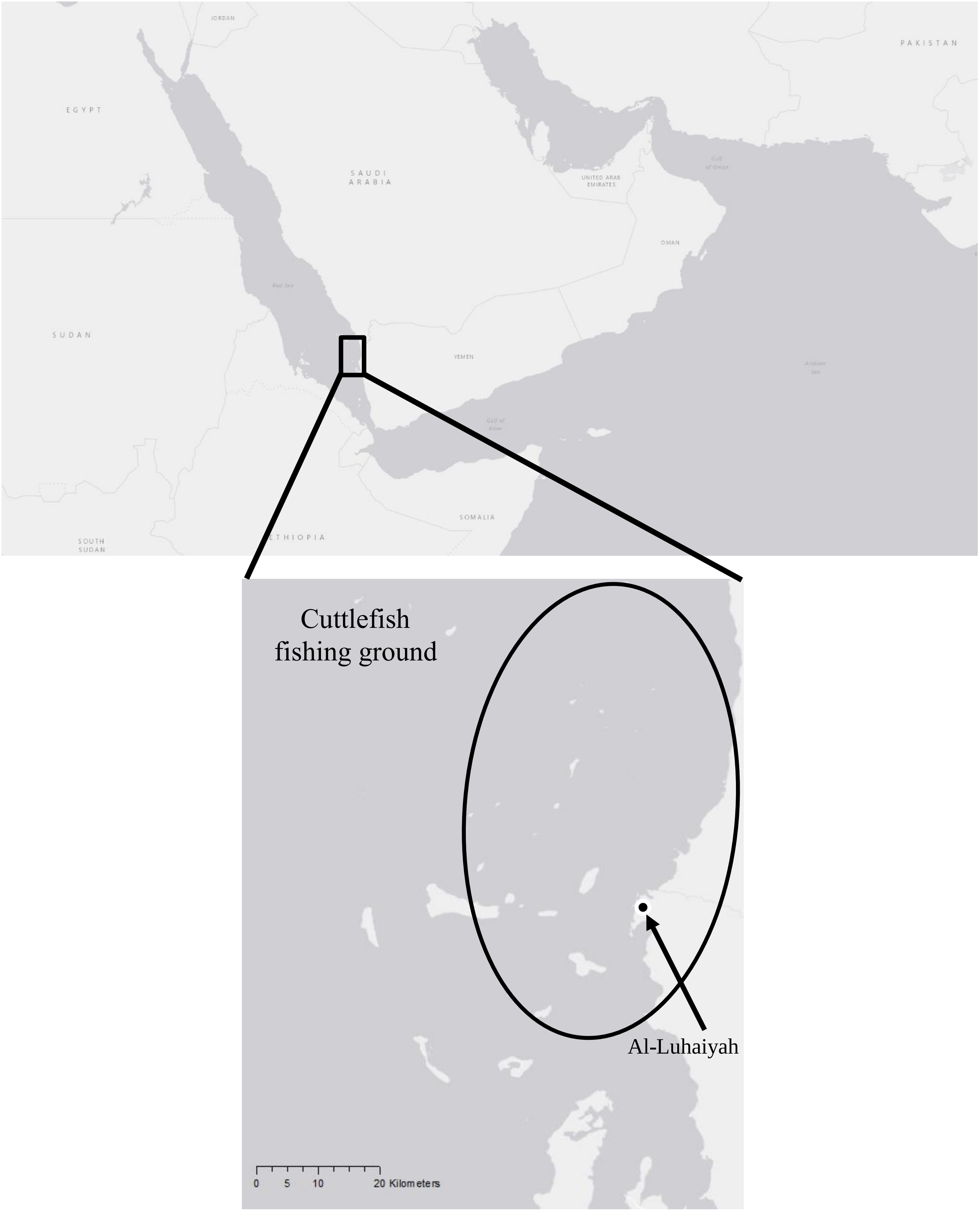


Figure 5.1. Maps showing the study area and the fishing grounds of Pharaoh cuttlefish off Al-Luhaiyah (lower map), 100km north of Hodeida, the main city on the Red Sea coast of Yemen (upper map)

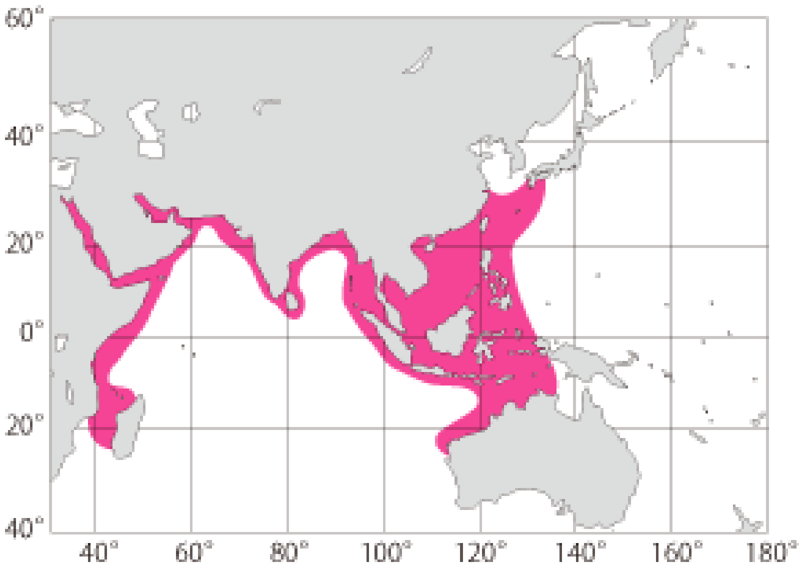


Figure 5.2. Map of the geographic distribution of Pharaoh cuttlefish extending from southwest Pacific Ocean to the whole Indian Ocean including the Red Sea (source: Okutani, 2005)

Specifications of the GPS logger

Memory 64MB: recording points 262,000

Automatic scheduled on/off

Battery life 160hrs (10+ days) – in case of 1-minute interval

Figure 5.3. Two types of data loggers with the same specifications of memory size, battery life and automatic on/off feature used for tracking boats of cuttlefish

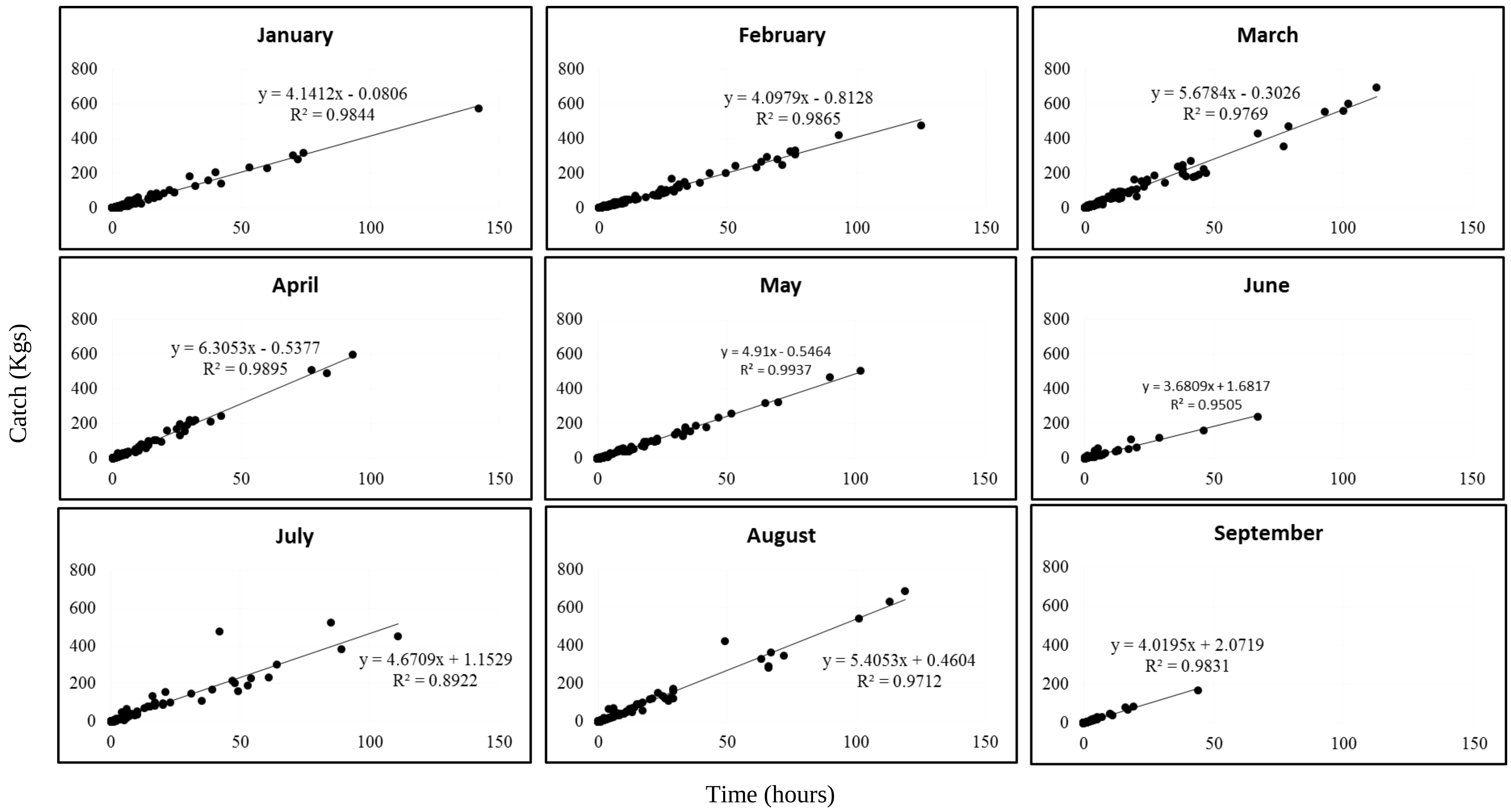


Figure 5.4. Graphs on relation between the catch and effort in different months from January to September 2013

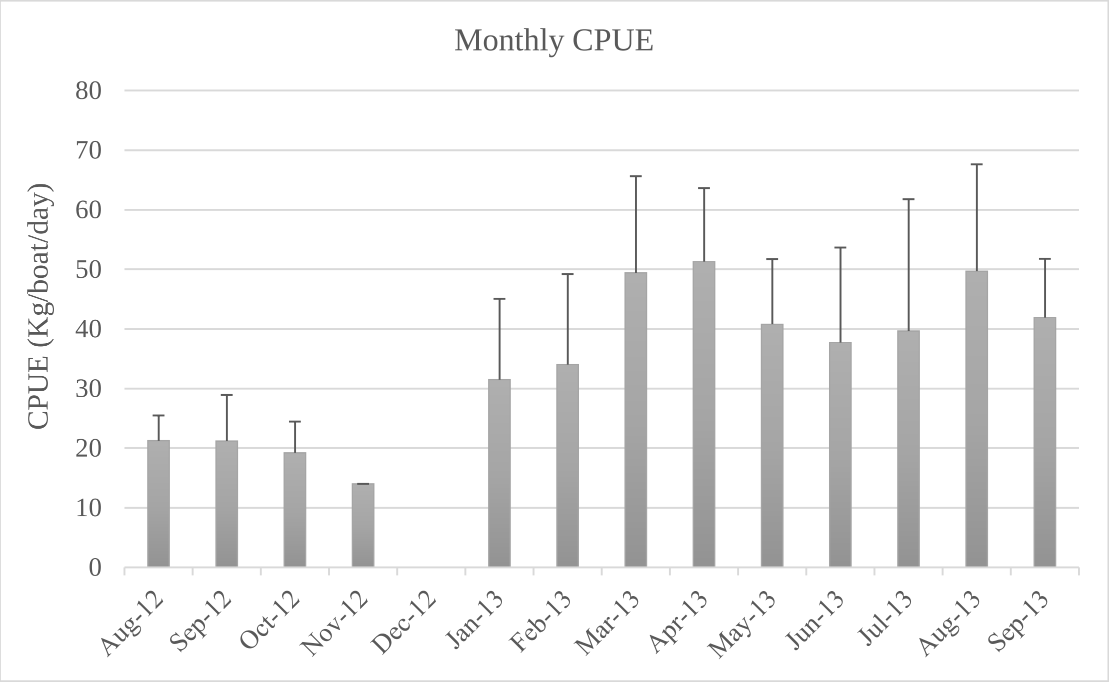


Figure 5.5. Time series of monthly CPUE (Kg/boat/day) from August 2012 to September 2013

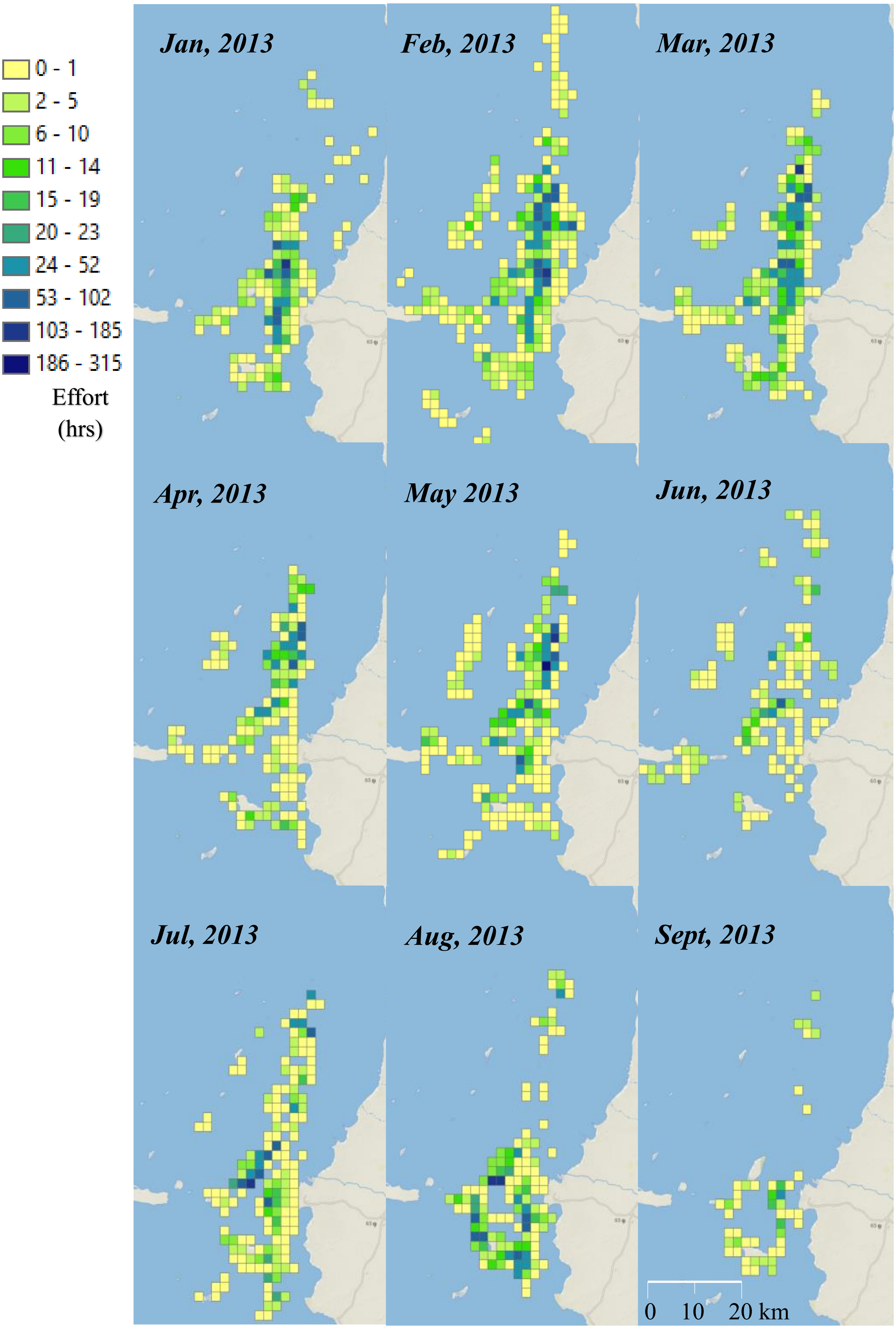


Figure 5.6. Monthly spatial distributions of Effort$_{polygon}$ (hrs fished/polygon) for pharaoh cuttlefish fishery from January to September in 2013

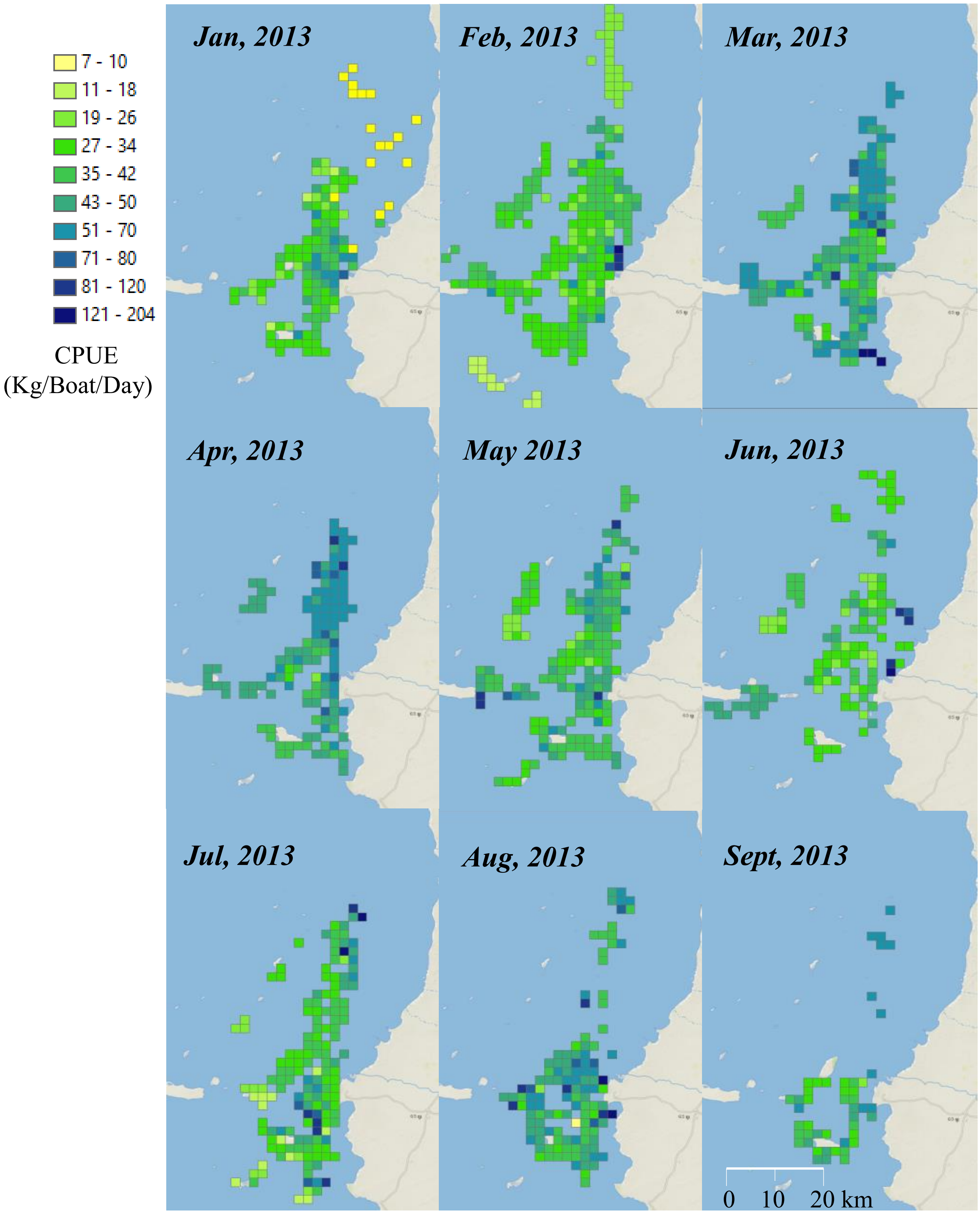


Figure 5.7. Monthly spatial distributions of $CPUE_{polygon}$ (Kg/Boat/Day) for pharaoh cuttlefish fishery from January to September in 2013

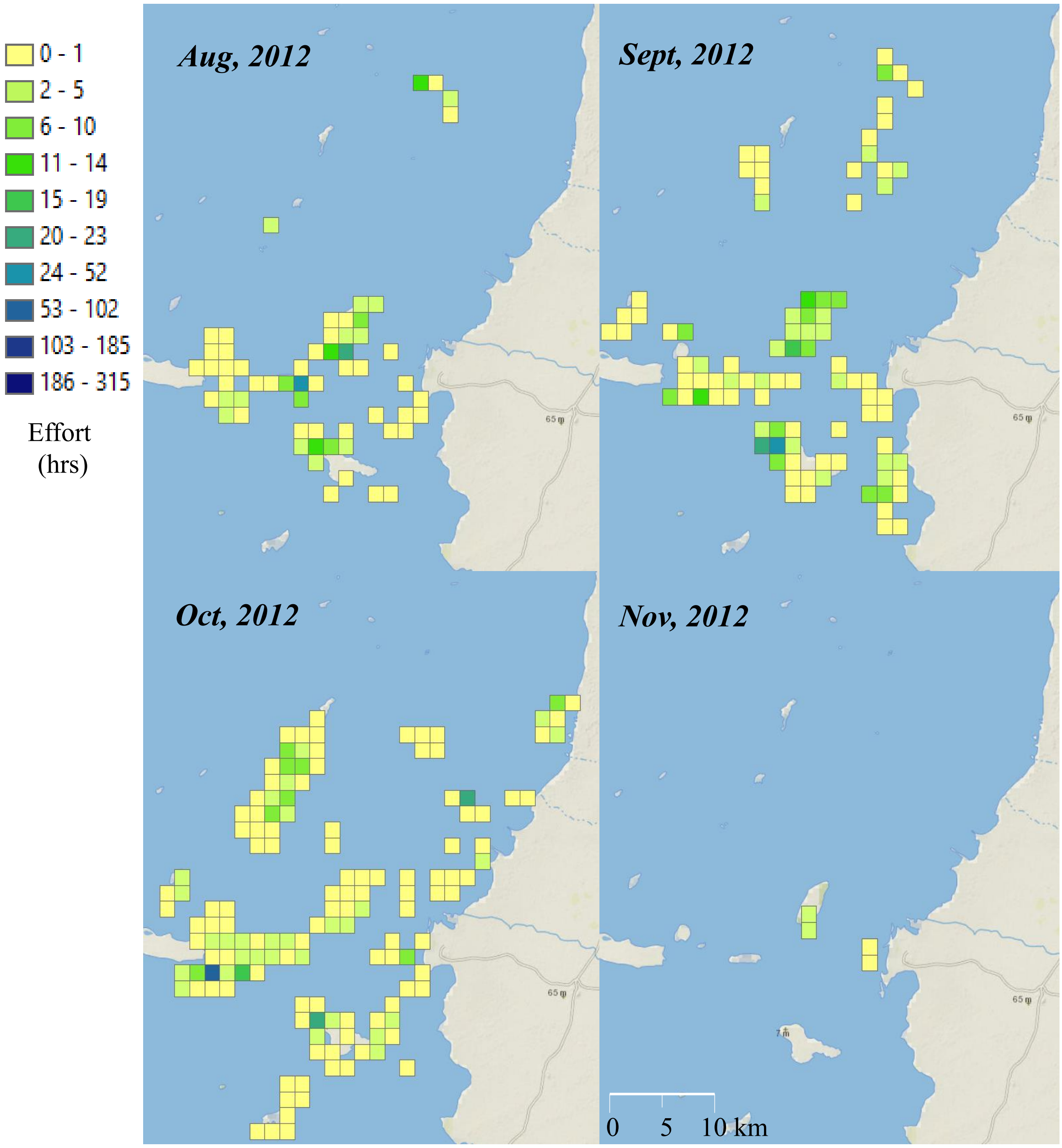


Figure 5.8. Monthly spatial distributions of Effort$_{polygon}$ (hrs fished/polygon) for pharaoh cuttlefish fishery from August to November in 2012

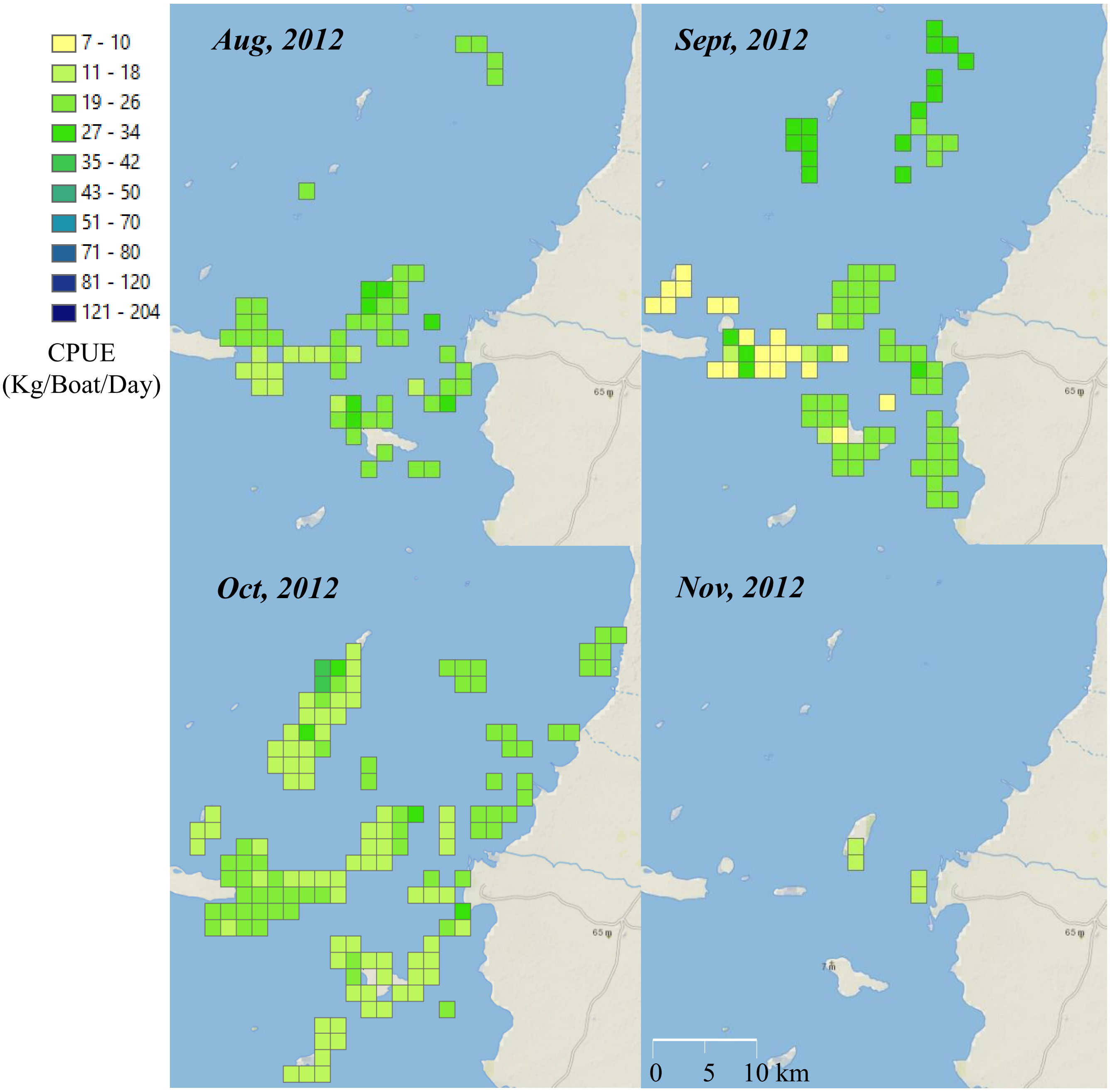


Figure 5.9. Monthly spatial distributions of $\text{CPUE}_{\text{polygon}}$ (Kg/Boat/Day) for pharaoh cuttlefish fishery from August to November in 2012

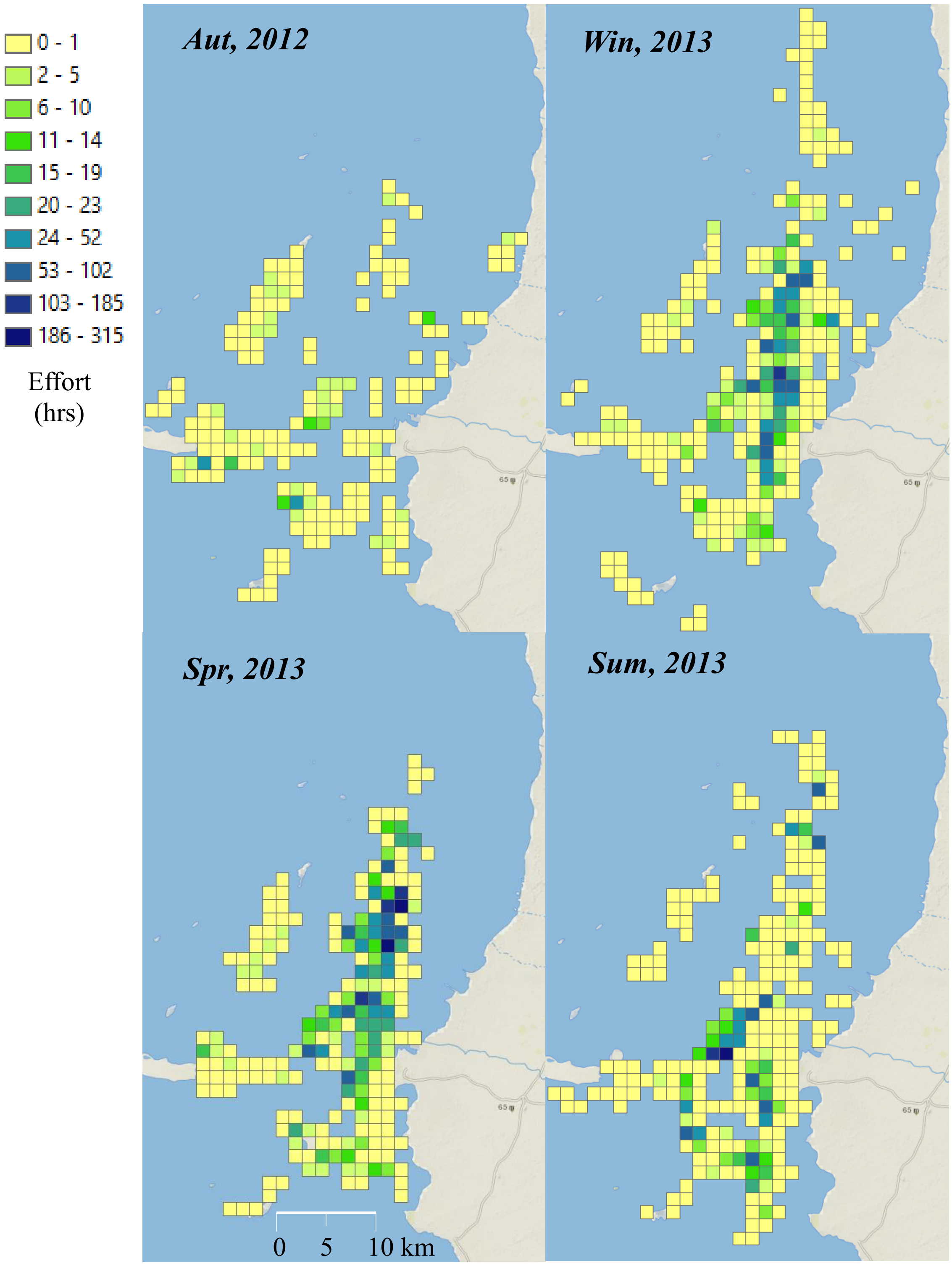


Figure 5.10. Seasonal spatial distributions of Effort$_{\mathrm{polygon}}$ (hrs fished/polygon) for pharaoh cuttlefish fishery in 2012 and 2013

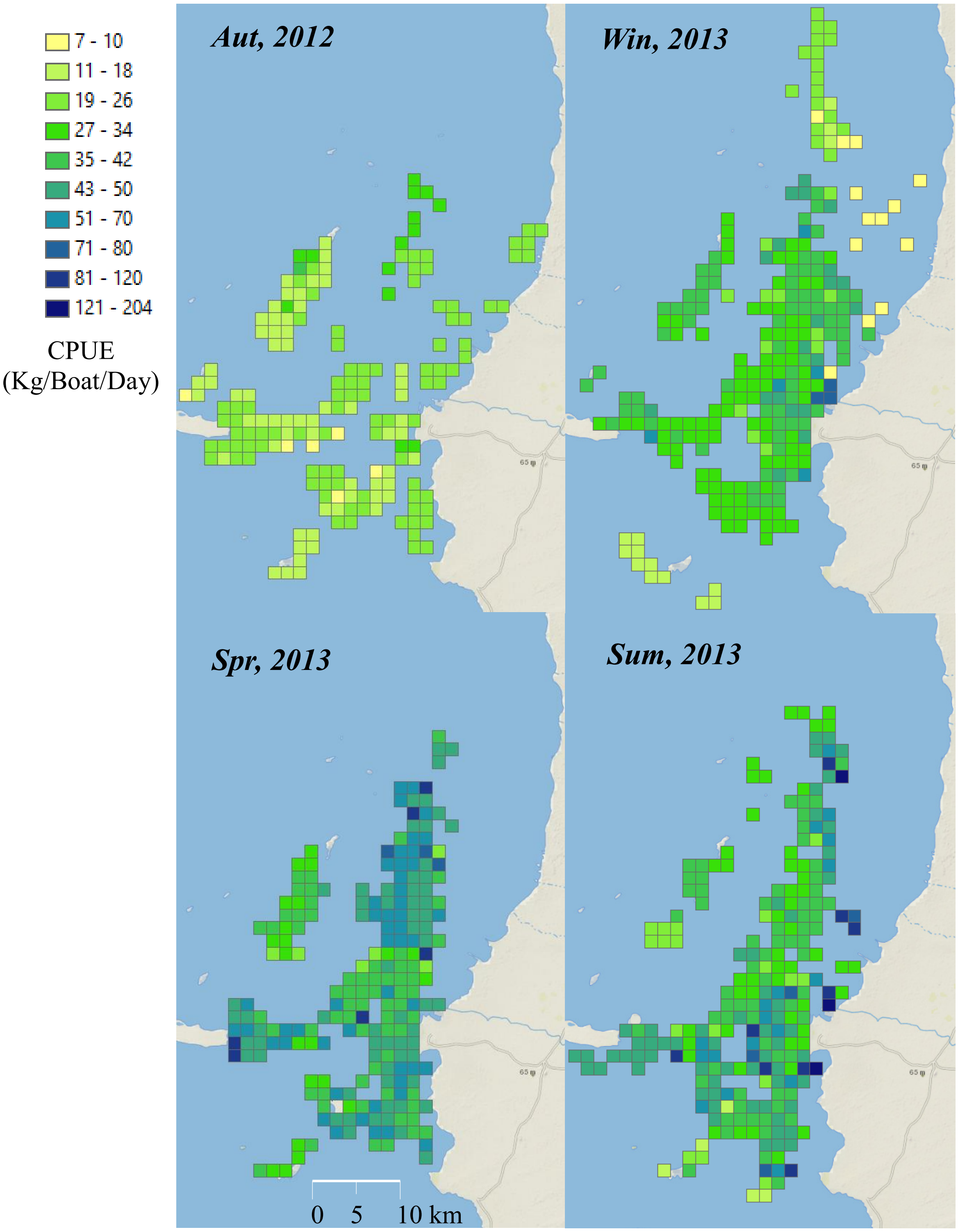


Figure 5.11. Seasonal spatial distributions of $\mathrm{CPUE}_{\mathrm{polygon}}$ (Kg/Boat/Day) for pharaoh cuttlefish fishery in 2012 and 2013

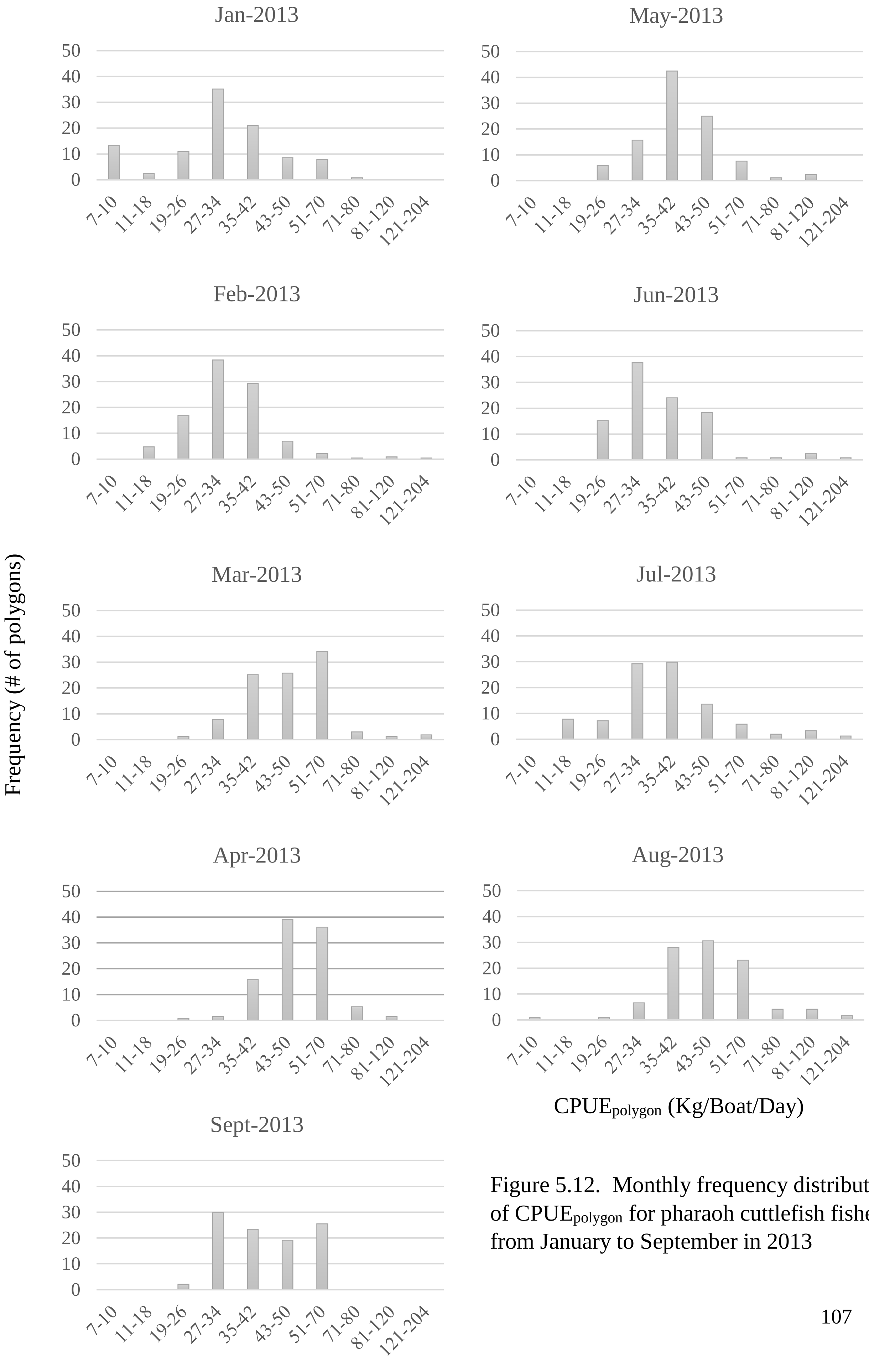


Figure 5.12. Monthly frequency distributions of CPUE$_{polygon}$ for pharaoh cuttlefish fishery from January to September in 2013

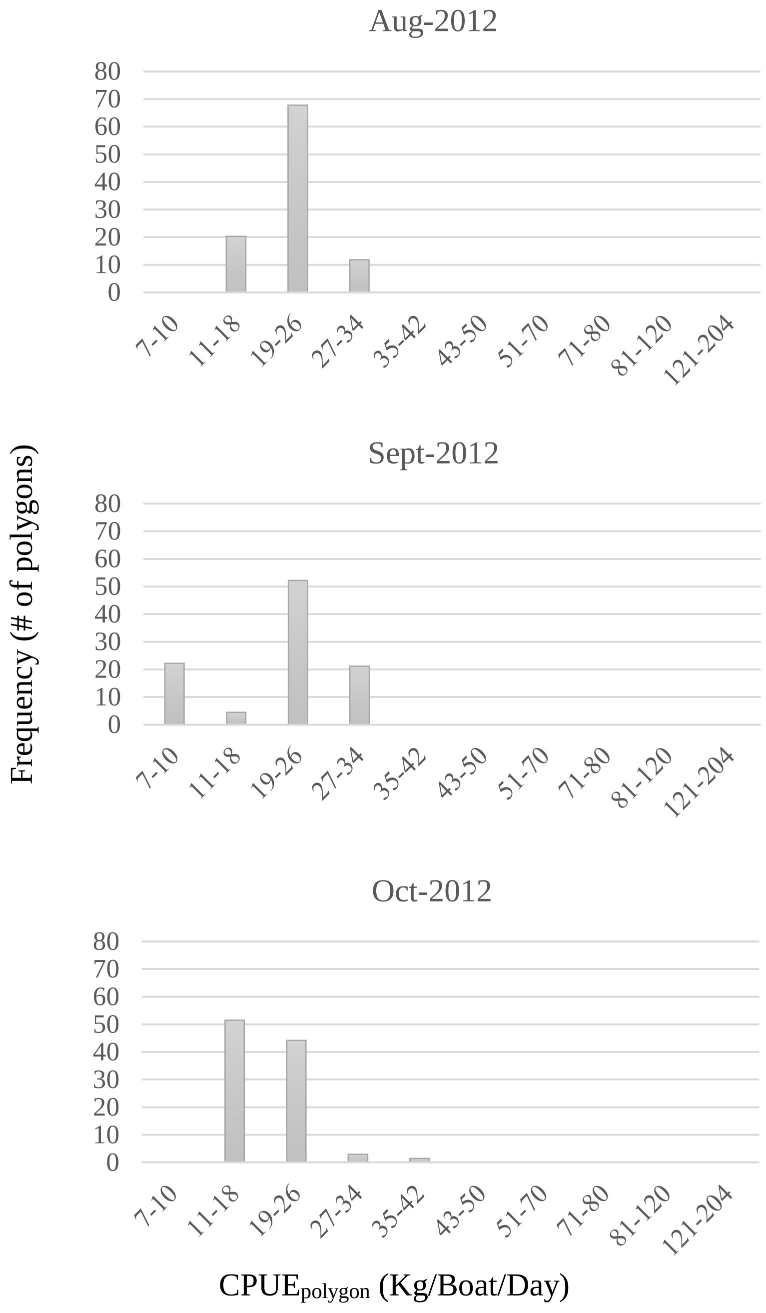


Figure 5.13. Monthly frequency distributions of CPUE$_{polygon}$ for pharaoh cuttlefish fishery from August to October in 2012

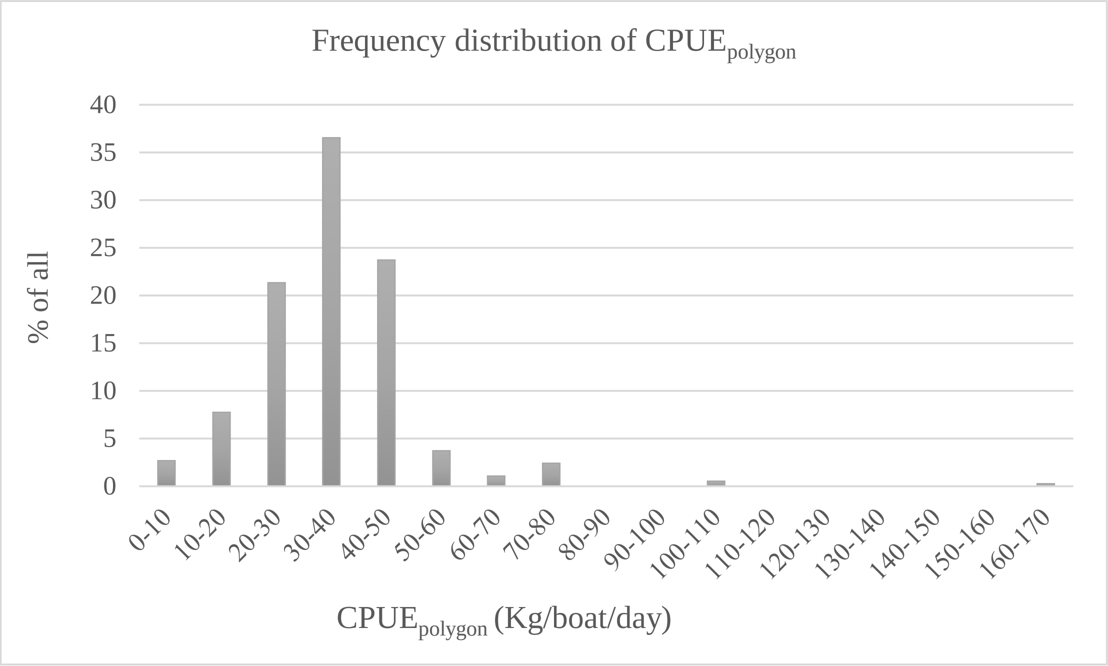


Figure 5.14. Frequency distribution of CPUE$_{polygon}$ of the whole study period for pharaoh cuttlefish fishery

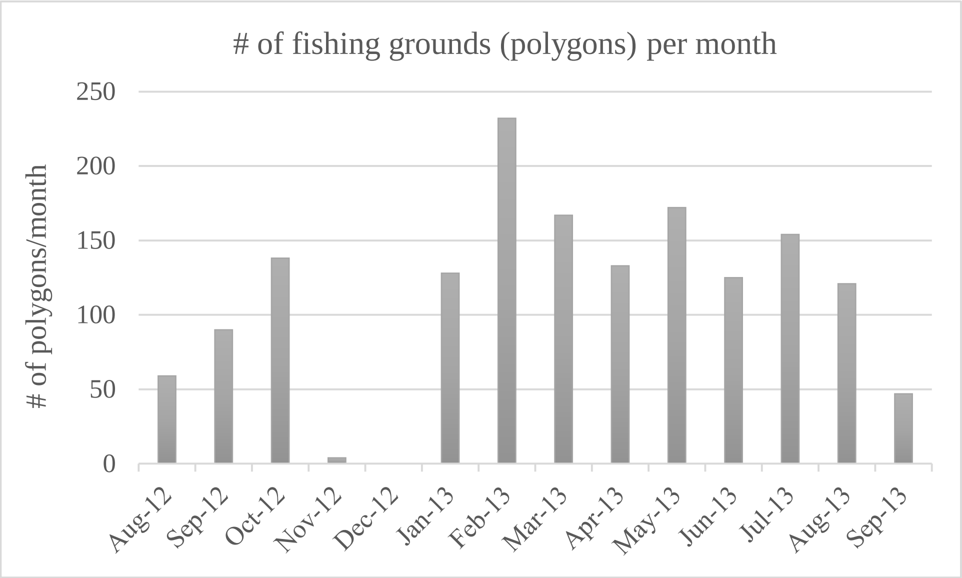


Figure 5.15. Number of fishing grounds (polygons) visited by fishermen per month from August 2012 to September 2013

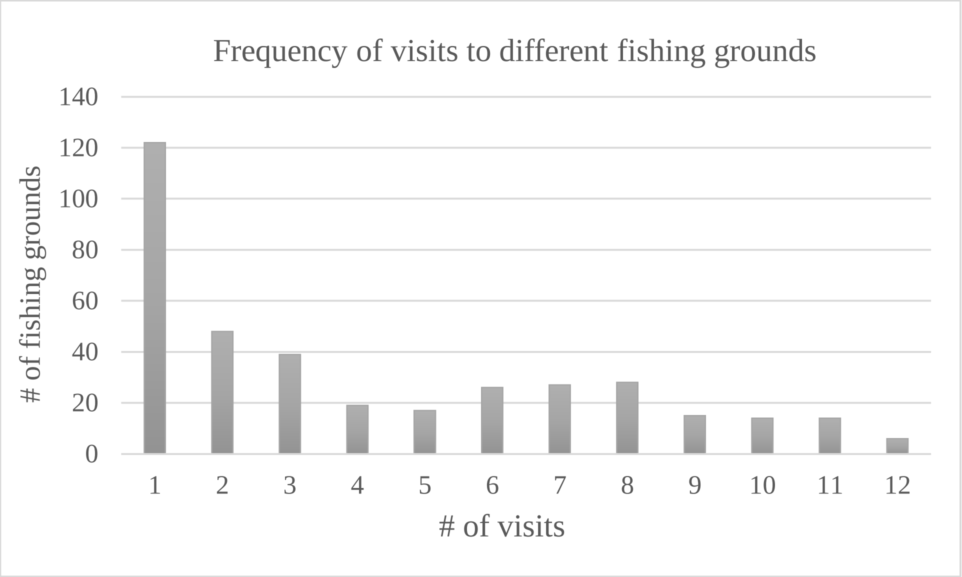


Figure 5.16. Frequency distribution of visits to different fishing grounds (polygons) for pharaoh cuttlefish fishery during the whole study period. Visits of more than one fisherman to a polygon in a specific month is counted as one polygon

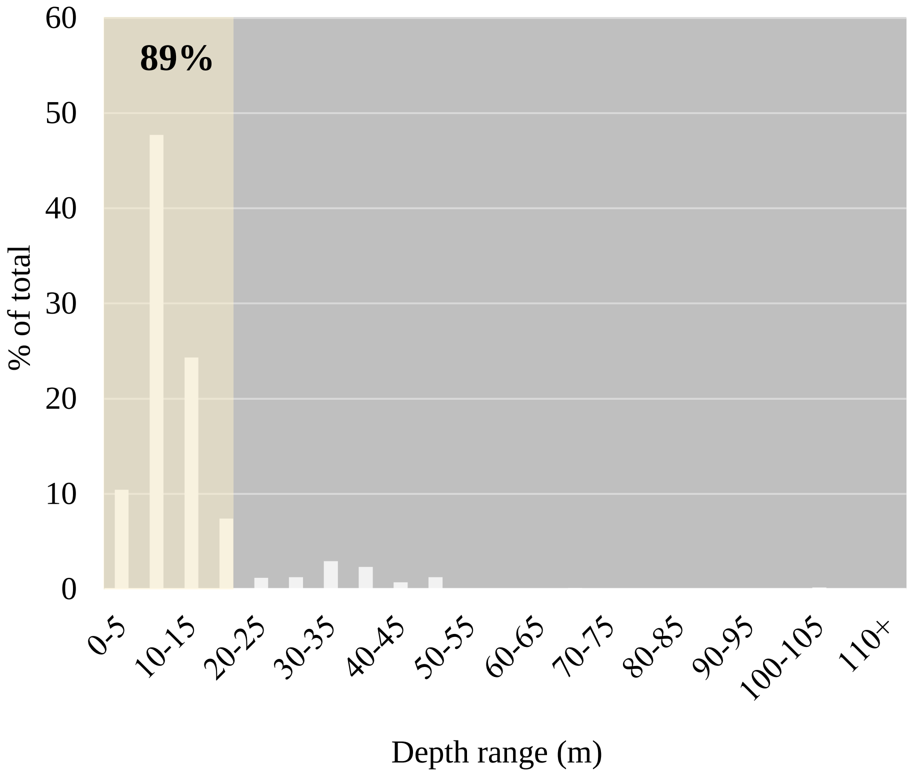


Figure 5.17. Frequency distribution of bottom depths at the fishing locations

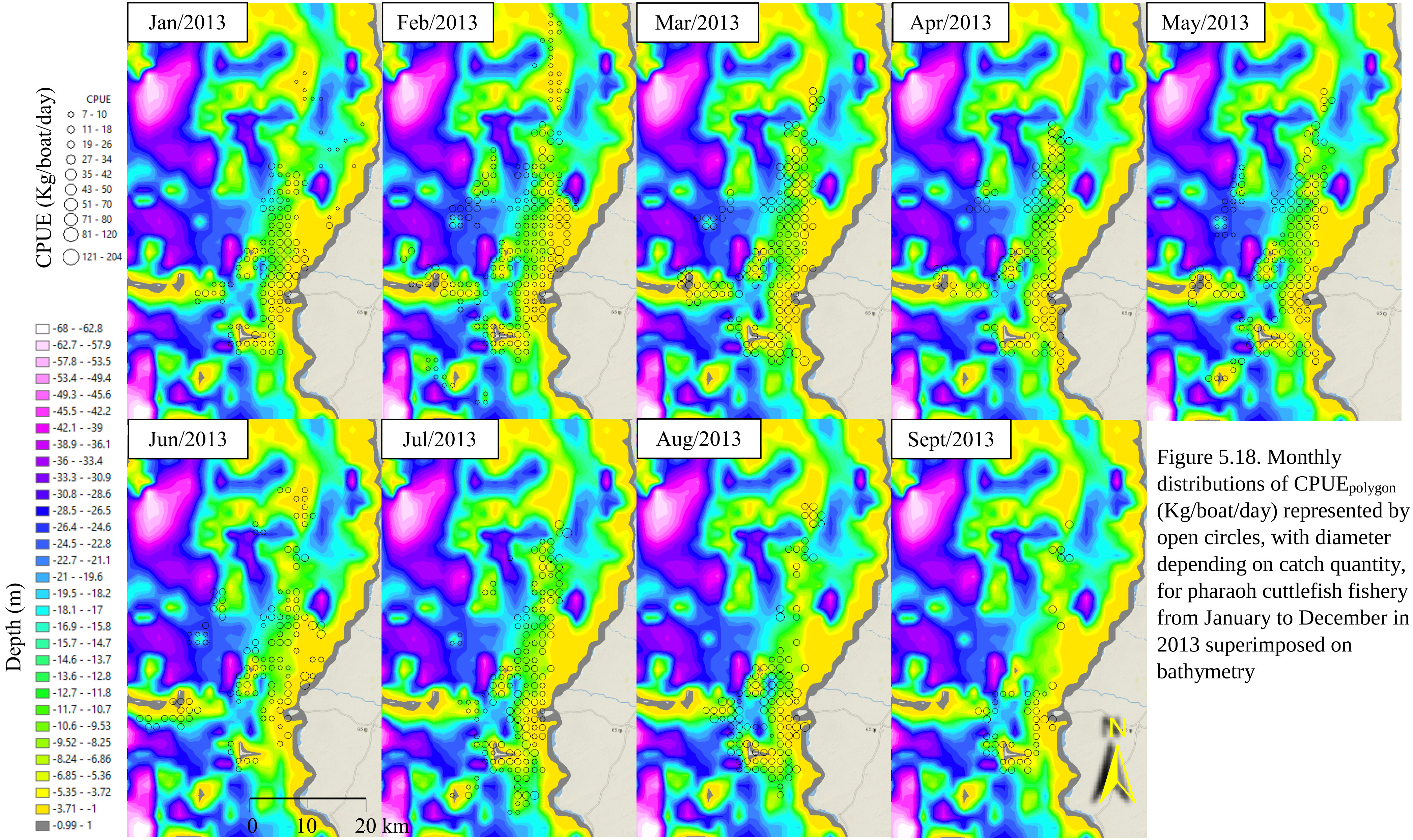


Figure 5.18. Monthly distributions of CPUE$_{polygon}$ (Kg/boat/day) represented by open circles, with diameter depending on catch quantity, for pharaoh cuttlefish fishery from January to December in 2013 superimposed on bathymetry

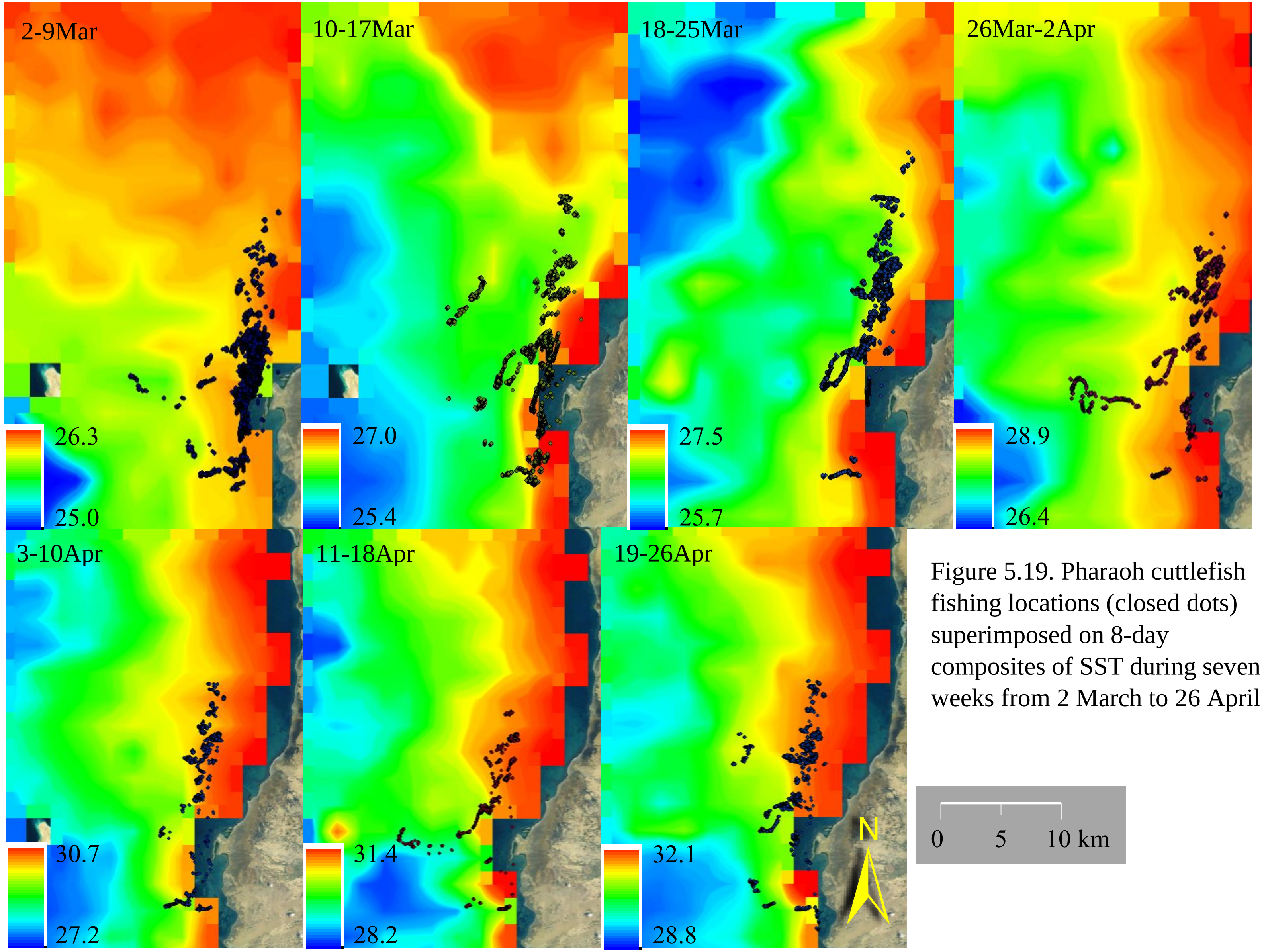


Figure 5.19. Pharaoh cuttlefish fishing locations (closed dots) superimposed on 8-day composites of SST during seven weeks from 2 March to 26 April

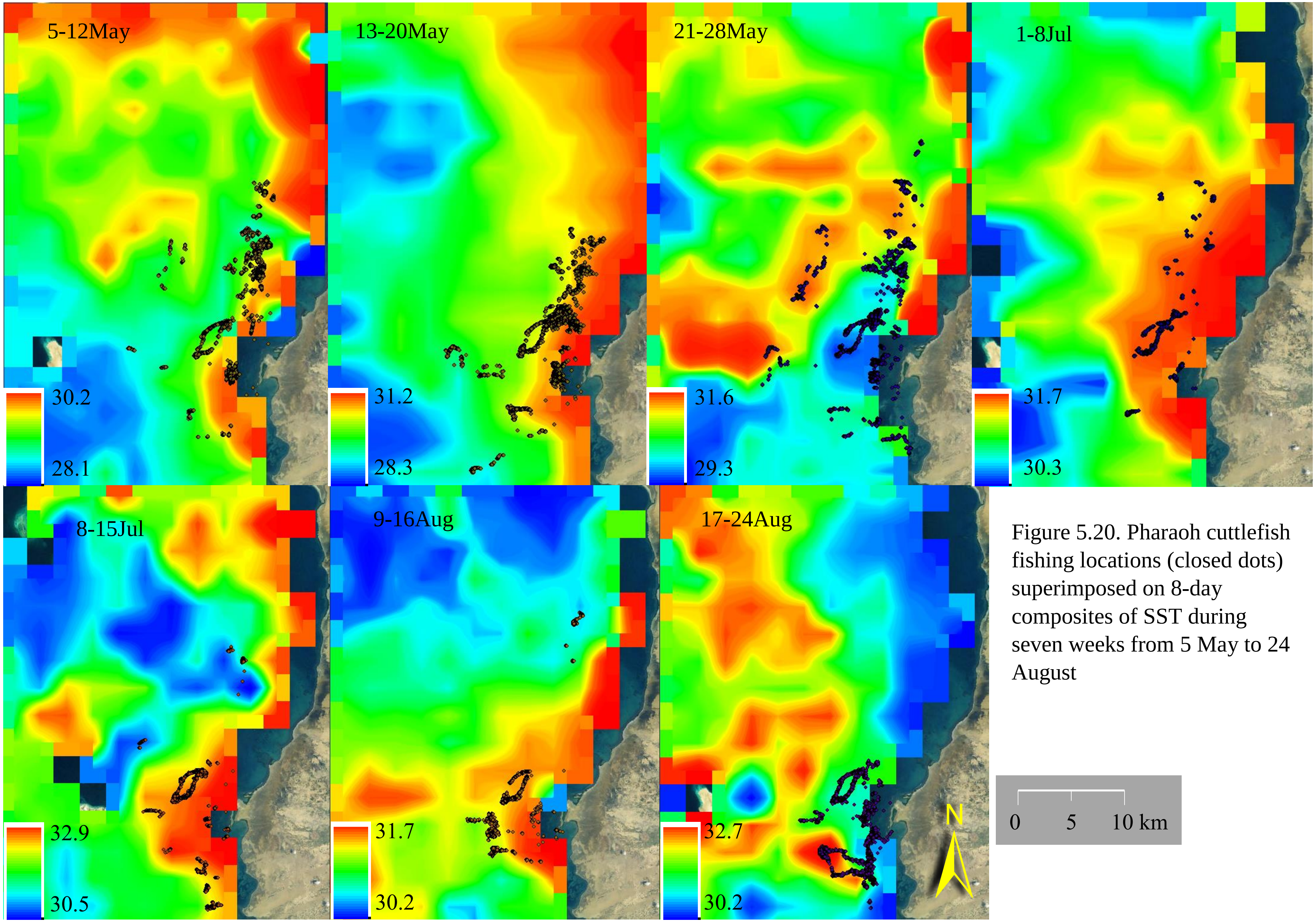


Figure 5.20. Pharaoh cuttlefish fishing locations (closed dots) superimposed on 8-day composites of SST during seven weeks from 5 May to 24 August

CHAPTER 6

GENERAL DISCUSSION

6.1. Fisheries management in Yemen

FAO Code of Conduct for Responsible Fisheries and other international agreements have introduced the Ecosystem Approach to Fisheries as a management tool to improve fisheries management and combat illegal, unreported and unregulated (IUU) fishing. However, management strategies of the fisheries sector in Yemen are still beyond the mainstream of modern fisheries policy. The lack of fisheries management plans is attributed to the weak knowledge base of the resources, which is reflected in unreliable statistics, unknown stock status, and weak governing system of the fisheries. The legislation provides the basis of penalties for violations, which have being relatively strengthened by issuing the law no. 2/2006. However, infringements are still common because the compliance of fishermen is low or lacking. Moreover, enforcement of laws and regulations controlling IUU fisheries is weak or absent because of an insufficiency of controlling systems such as coast guards and patrol vessels. Thus, the lacks of compliance and enforcement are due to poor governance of the sector resulting from weak infrastructures and widespread corruptions among the policymakers and judiciary authorities. However, it is necessary to manage fisheries resources using the most appropriate approaches. How do we obtain data relating to fisheries resources under insufficient scientific infrastructures? This study aims to respond to this question.

6.2. Involvement of fishing boats in voluntary data collection

Fisheries as well as wild life scientists regularly require data concerning resources. Under limited research fund, scientists need to respond to these requirements routinely. Therefore, it is necessary to develop novel approaches to collect the data at minimum cost and at regular periods. In developing countries, it is very difficult to monitor resources by scientists because of weak or lack of infrastructures. Hence, this study presents a novel approach to monitor small-scale fisheries by using GPS, GIS and remote sensing data, which can be used in developing countries. Moreover, to minimize data collection costs, fishery data were collected in cooperation with fishermen. Participation of fishermen was voluntary and keeping a good relation with them appeared to enhance the chances of success of data collection.

6.3. Exploitation of fishermens' knowledge for scientific research

The majority of resource users, especially those in developing countries, are illiterate. Scientists concerned with conservation issues are not part of these social-ecological systems. Moreover, stakeholders are rarely involved in planning and management and less represented in decision-making process. The knowledge possessed by those endogenous people has a great potential and can contribute to advance our knowledge of natural ecosystems because a continuous record of knowledge is gathered by those people for generations and inherited from one generation to the next. Stakeholders are unaware of this knowledge and scientists underestimate its potential and rarely try to explore it. For example, fishers know that cuttlefish come to the shore for spawning twice a year as mentioned in Chapter 5. Thus, it is very important for scientists to systematically collect this knowledge with standardized methods for interviewing and archiving it for mining these data. Stakeholders need to understand that their experiences as resource users are helpful and meaningful for their resource management.

The contribution of traditional knowledge held by fishers can be significant in data limited situations. In data poor fisheries, baseline information on the key fish species are lacking. However, the knowledge possessed by fishers on species biology, ecology, distribution and abundance can be valuable. Several information obtained from fishermen in this study have provided answers to many questions which were raised throughout the study. Although some studies on similar or related species may have been already conducted in different geographical areas, their results do not necessarily apply to our study area. The knowledge of fishermen about the biology and ecology of fisheries resources and resource use in the past and present can be regarded as an information bank to aid scientific research. Such traditional knowledge is qualitative more than quantitative, dispersed more than organized. In order to benefit from this valuable knowledge, it is necessary to find appropriate methods to collect, quantify and validate it to increase its usability in the scientific context and to understand where traditional knowledge meets with scientific knowledge.

Several examples from the current study support this notion. Fishermen’s knowledge about cuttlefish spawning times, suitable spawning habitats and effect of water quality on catchability are examples of their knowledge, which helped to understand some trends observed in this study.

6.4. Small-scale vs. large scale fisheries

Most of studies which utilize satellite remote sensing data to investigate environmental variability on species have come from large-scale fisheries, in which location data are available from VMS and corresponding catch from obligatory logbooks hold by these vessels. Large-scale fishing activities, such as in most developed countries, usually involve smaller number of large vessels. Hence, it is easier to monitor their spatial activity using the VMS, to monitor their capacity using such indices as total allowable catch (TAC) and to monitor the compliance by onboard observers, landings inspection, or any other enforcement tools. In contrast, it is difficult to use the same management systems and tools for small-scale fisheries in which a large number of fishing boats are harvesting smaller fish stocks widely distributed along the coast. In addition, these fisheries target multi-species (many different species) with multi-gears (different gears) at different seasons and in different areas. Fishermen commonly change the target species and/or fishing gear very often. Moreover, dispersed fishing activities complicate data acquisition by scientists. With all these features of small-scale fisheries, it is difficult to monitor using the same systems and tools used in large-scale fisheries. Here it is necessary to take different approaches incorporating increased participation of fishermen in fisheries management through negotiations and fishermen involvement in decision making. In this connection, it is also desired to invest in mechanisms which encourage compliance and strengthen enforcement.

6.5. Introduction of high resolution GPS to map activities of small-scale fisheries

VMSs used for large-scale fisheries generally provide locations of fishing boats at low spatial and temporal resolutions such as once every two hours, once every one-hour or once every 20 minutes. However, data obtained at low spatial and temporal resolutions do not reflect much information about the fishing activities in coastal waters, where environmental conditions change rapidly temporally and spatially. Hence, it is difficult to draw concrete conclusions on the spatial and temporal variability of fishing grounds formation and species distributions in coastal waters. In addition to the high cost of VMSs, their coarse resolutions are not suitable to monitor small-scale fishing activities in coastal waters of most developing countries. In contrast, the advent of high-resolution GPS data loggers, with a large memory size, extended battery life and affordable prices, has enabled the deployment in small-scale fisheries. Such high resolution GPS loggers enable the investigation of the fishing activity at high spatial and temporal resolutions and this fit the heterogeneous nature of fish, fisheries and resource users.

This study proposed use of fishers and their fishing boats as research platforms for monitoring resources. Combined GPS and catch data can provide important information on the resources. The cost of 40 GPS loggers is less than 5000 USD. Although ArcGIS is used in this study, FAO and other international organizations have developed free GIS softwares. Therefore, this method is practical and easily applicable to fisheries resources in developing countries.

6.6. Role of remote sensing in fisheries management

In the context of an ecosystem approach to fisheries, satellite remote sensing of marine environments provides a valuable source of information on the interactions between fish species and their environments. Including environmental effects on fish catchability and distributions of fishing locations in estimation of abundance of species targeted by fisheries would improve scientific understanding of state of fish stocks and establishing management strategies for fish stocks. Satellite images are provided globally, daily and systematically with a moderate spatial resolution. They provide a good data source for incorporating habitat considerations into marine fish population dynamics. Identifying spawning and/or feeding grounds based on satellite remote sensing is also a prerequisite for spatially orientated management measures, such as the implementation of marine protected areas (Druon, 2010). The most important point is that information obtained by satellite remote sensing are generally free and downloaded via the internet. Thus, the information is available for public use even in developing countries that have no satellites.

The use of satellite remote sensing increase our ability to track and predict the spatial dynamics of marine species using key environmental parameters. By incorporating satellite data into environmental-niche models, it is possible to reproduce the current distribution and temporal fluctuations of a given species by estimating suitable physical and biological conditions (Chassot *et al.*, 2011). Finally, this may contribute to sustainable use of fisheries resources.

6.7. Implications for fisheries management

Essential information and knowledge on stock status are not available in most developing countries. Simple and inexpensive methods of fish abundance estimation are desired in such situations. This study developed a novel approach to monitor fishing effort distributions in time and space with the use of mobile GPS loggers. High-resolution data enabled us to detect the exact fishing locations and to estimate fishing effort at fine scales. The GPS data of purse seines have included a variety of helpful information. The diameter of fishing haul gave a good indication of the size of fishing gear used. After-haul drifting chart gave an indicator of wind speed and direction. Speed chart of fishing boat indicated the optimum speed for fishing efficiency. The high correlation between satellite derived chlorophyll and Indian mackerel distribution introduces opportunities to investigate the spatio-temporal distribution of this species and will aid to formulate fishery management plans. The concentration of hauling locations around sea surface temperature fronts can be utilized to characterise the potential fishing zones and this will greatly minimize search costs and the time spent in the sea for fishermen. Using remotely-sensed information, it is possible to investigate the interannual fluctuation in abundance of pharaoh cuttlefish to predict future population sizes and modify management measures. The spatio-temporal distribution of CPUE of this species revealed their aggregation sites and the coincident overfishing of cuttlefish during this study. The results suggest the use of spatial and/or temporal ban on fishing for cuttlefish in the critical spawning and nursery areas of this species.

Finally, this study highlights the necessity of involvement of fishermen in the collection of data for scientific purposes. Fishing boats can play as platforms for the collection of data on the resource use. This new approach will minimize research costs and have the potential to be a sustainable source for data collection for small-scale fisheries not only in developing countries but also in developed countries.

6.8. Essential fishing habitat

The combined use of GPS, GIS and remote sensing techniques has enabled the characterization of essential fishing habitat for both the Indian mackerel and pharaoh cuttlefish. The relation of fishing data with environmental data has enabled us to analyse the formation of fishing grounds and to determine the important factors, which control fishing habitat location. Chlorophyll concentration and SST fronts appeared to be the most important factors, which affect the distribution of the Indian mackerel. Bottom depth appeared an important factor in the distribution of pharaoh cuttlefish. Moreover, bottom type, i.e., sponge habitats, determines the geographic distribution of pharaoh cuttlefish.

PhD Thesis (Summary)

A Novel Approach for Monitoring Small-Scale Fisheries with GPS, GIS, and Remote Sensing Techniques

(GPS，GIS，リモートセンシングを用いた小規模漁業モニタリングの新しいアプローチ)

Natheer Mohammad Abdulwaheed Alabsi

ナゼイル　ムハンマド　アブドルワヒード　アルアブシ

Small-scale fisheries worldwide are less investigated although they provide most of the production from the sea to local people and secure employment for 98% of fifty one million fishers in the world. Most of these fisheries are located in developing countries where scientific researches in fisheries management lack official support and fisheries scientists are underqualified. Accordingly, it is difficult for scientists and fishery managers in these countries to apply the same approaches used for large-scale fisheries in developed countries. Tropical small-scale fisheries are highly heterogeneous with respect to a wide variety of fisheries characteristics. It is necessary to examine the heterogeneities of small-scale fisheries, which haven't been investigated. For this purpose, a novel approach using GPS, GIS and remote sensing techniques was developed in this study. Yemen's small-scale fisheries as an ideal type of a small-scale fishery were chosen as a case study to explore the potential of the approach for monitoring of small-scale fisheries. The recent decline of fish resources of Yemen coupled with uncontrolled growth of fishing fleets are major obstacles for development of sustainable fisheries. Both stock status and current exploitation levels of major fisheries are unknown. Lack of scientific researches and effective management policies jeopardizes the sustainability of Yemeni small-scale fisheries and coastal ecosystems. In order to conserve the coastal fisheries resources and ecosystems on which coastal inhabitants are dependent for subsistence, it is necessary to determine the exploitation levels of fisheries resources. Spatio-temporal distributions of fishing efforts and catch per unit effort (CPUE) can provide a detailed picture of exploitation patterns and pressure levels on different fish stocks. The details are described as follows.

The study describes the status of Yemeni fisheries and highlights their current problems and priority research areas. It also analyses the different components of the fisheries management system of Yemen and highlights its strengths and weaknesses. Yemen’s coastline exceeds 2,500 km extending along the Red Sea, Gulf of Aden and Arabian Sea. Stock status of commercially exploited fish species is unknown and no active management plans enforced anywhere in Yemen. Furthermore, fishing efforts, namely number of fishing boats, have increased four-fold between 2000 and 2010 while the CPUE has decreased significantly during the same period. According to official statistics, total fish production of Yemen has reached a peak of 256,000 tons in 2004 and thereafter dropped to 180,000 tons in 2007 and to 127,000 tons in 2008. To ensure sustainable exploitation in such data poor situations, it is greatly needed to study the characterization of fishing effort and fishermen’s use of resources and fishing grounds. This study aims to develop a novel approach for monitoring small-scale fisheries and their CPUEs, integrating GPS acquired location data of fishing boats, GIS that relate position data with catch and environmental data and remote sensing techniques that provide environmental data. Using this approach, we described the spatio-temporal distribution of fishing grounds and how the fishing grounds are formed and influenced by the environmental conditions and the implications for fishery management were explored. This study selected two representative small-scale fisheries from the Red Sea of Yemen.

The novel approach developed here is designed for obtaining positions of small-scale fishing boats and analysing fishing grounds with GPS, GIS software and satellite images of sea surface temperatures and chlorophyll monitored by MODIS satellites and provided by National Aeronautics and Space Administration, United State of America. The GIS software used bottom topography data of ETOPO1 for fishing ground analysis. The ETOPO1 is a one arc-minute global relief model of Earth's surface that integrates land topography and ocean bathymetry provided by National Geophysical Data Center, United States of America. Forty GPS loggers were used and one GPS logger was given to each voluntary boat, which reported catch of each trip during acquisition of boat positions with the logger. These data were analysed with GIS software (ArcGIS 10.0, ESRI). Catch data were collected on each trip, which include the catch composition by species and weight.

The novel approach was applied to a case study of Indian mackerel (*Rastrelliger kanagurta*) fisheries in Yemeni Red Sea to describe the spatio-temporal distribution of fishing grounds and to investigate the roles of environmental variables in the formation of fishing grounds and their dynamics in time and space. For this purpose, 20 GPS loggers were used to collect the data on boat location and speed at 5-seconds intervals for purse seine fishing gear targeting the Indian mackerel. The overall lengths of the boats belonging to the voluntary skippers were between 12 and 15 m. Fishermen used purse seine nets, which had an average horizontal length of 407 m and vertical depth of 16.3 m. Fishing is conducted only during the nighttime between sunset and sunrise and one trip is confined to only one night and the fishing usually stops from day 7 to day 17 during the lunar nights. Twenty GPS loggers were used for eight months to collect the position data on the Indian mackerel fishery. Fishing hauls were easily recognized with boat speed recorded by the high resolution GPS recordings. The mean number of fishing hauls per day was 2.65±1.4 hauls/day and the mean hauling speed (encircling speed) was 13.2 m/s. The mean catch/haul and mean catch/day were 98.6±70.4 kg and 212.5±154.5 kg, respectively. Geospatial analysis using GIS and remote sensing data and bottom topography showed that fishing grounds of Indian mackerel were concentrated in high chlorophyll waters and along the SST fronts. Especially in October, most of the catch originated from areas in inshore waters inside two semi-enclosed bays. Inshore movement of Indian mackerel was synchronized with the highest annual chlorophyll concentration. This indicates a specific behaviour of this species, probably associated with spawning which occur around this period.

The novel approach was also applied to a case study of pharaoh cuttlefish (*Sepia pharaonis*) in Yemeni Red Sea to describe their spatio-temporal distributions. The overall lengths of most fishing boats targeting this species were 7-m. Fishermen used a hook and line with artificial lures to fish cuttlefish. Data on more than 2000 fishing trips of 40 voluntary boats between June 2012 and May 2014 were collected by providing the volunteers with GPS loggers. Boat positions were recorded using the GPS logger at 1-minute intervals for monitoring fishing activities of boats targeting pharaoh cuttlefish. Boat positions data were processed with the GIS software to remove non-fishing periods based on boat speeds below 3 km/hr because the boats are usually drifting while fishing. The catch of every trip measured at a landing port was divided on all the fishing points of the trip according to the time. Maps of the monthly and seasonal spatio-temporal distribution of CPUEs showed that a time series graph of monthly CPUE had two peaks, one in March/April and the other in August/September. The cuttlefish in the study area has two fishing seasons per year, the first started from mid-January until May and the second from July until September. Distribution of fishing activities was highly confined to shallow bottom depths within 20 m. Since *Sepia* sp. live in offshore waters and move to the coastal areas for spawning, this suggests that the two peaks in March/April and in August/September correspond to two spawning times of this species, which may produce two different cohorts of cuttlefish.

Essential information and knowledge on stock status are not available in most developing countries. Simple and inexpensive methods of fish abundance estimation are desired in such situations. This study developed a novel approach to monitor fishing effort distributions in time and space with the use of mobile GPS loggers. High-resolution data has enabled us to detect the exact fishing locations and to estimate fishing effort. The GPS data of purse seines have included a variety of helpful information. The diameter of fishing haul gives a good indication of the size of fishing gear used. After-haul drifting chart gave an indicator of wind speed and direction. Speed chart of fishing boat indicates the optimum speed for fishing efficiency. The high correlation between satellite derived chlorophyll and Indian mackerel distribution introduces opportunities to investigate the spatio-temporal distributions of this species and will aid to formulate management plans. The concentration of hauling locations around sea surface temperature fronts can be utilized to characterise the potential fishing zones and this will greatly minimize search costs and the time spent in the sea for fishermen. The spatio-temporal distribution of CPUE of pharaoh cuttlefish revealed their aggregation sites and the coincident overfishing during this study. The results suggest the use of spatial and/or temporal ban on fishing for cuttlefish in the critical spawning and nursery areas of this species.

Finally, this study highlights the necessity of involvement of fishermen in the collection of data for scientific purposes. Fishing boats can play as platforms for data collection on the resource exploitation. This new approach will minimize research costs and give an opportunity to collect data on small-scale fisheries not only in developing countries but also in developed countries.

Acknowledgements

First, I would like to express my sincere gratitude to my parents for raising me to have confidence, for praying for my success and all the support they have provided me over the years was the greatest gift. I have been fortunate to have a wonderful supportive wife that has helped me focus on my study and shared my worries.

I would like to express my deepest gratitude to my supervisor, Prof. Komatsu Teruhisa, for his generous guidance, great support, inspiration and constructive feedback during the work on my PhD program. I have been fortunate to have the opportunity to work as part of his team and to gain scientific knowledge and technical skills in the field of oceanography. He has given me plenty of opportunities to participate in various oceanographic surveys. I am also thankful to him for carefully reading and commenting on my manuscripts. His profound knowledge, innovative ideas and encouragement helped me to overcome many difficulties faced throughout the years in Master’s and Doctoral programs.

I would like also to express my gratitude to Professors Kunio Shirakihara and Yutaka Michida and Associate Professor Kosei Komatsu, Atmosphere and Ocean Research Institute, the University of Tokyo, and Dr. Tom Nishida of National Research Institute of Far Seas Fisheries, Fisheries Research Agency and the current president of the Indian Ocean Tuna Commission, for proofreading and reviewing my thesis and making a number of helpful tips and suggestions.

I would also extend my sincere gratitude to my old colleagues, Mushtaq Abker and Makbool Abu Hashish of Faculty of Marine Science and Environment, Hodeidah

University, Yemen, for their great support in data collection during the period from 2011 to 2014. Thanks also extend to all fishermen from Hodeidah fishing port and from Al-Luhaiyah for passionately participating in data collection, carrying the loggers and reporting the fishery data.

I wish to express my appreciation to Mr. Niazi Assalami, from the Ministry of Fish Wealth, staff of the National Information Center, and Mr. Muafaq Alabsi from the Red Sea Fisheries Authorities of the Republic of Yemen for providing the data, the legislations, and the reports used in different parts of this thesis.

I acknowledge the NOAA CoastWatch Program and NASA's Goddard Space Flight Center, OceanColor Web for making satellite data available for the public. “Maps throughout this thesis were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit www.esri.com.”

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