THE UNIVERSITY OF HULL

Assessment and management of the Abalone (*Haliotis mariae*, Wood 1828) stock in the Omani waters

Being a Thesis submitted in partial fulfilment of the requirements for the Degree of

Doctor of Philosophy in
Fisheries Studies

in the University of Hull

By

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SUMMARY

This study investigates the status of Abalone fishery (*Haliotis mariae*) in the southern region of Oman. This fishery has been an important and valuable resource to both the population in this region as well as for the country. The fishery began around 1970 and produces annually between 29-56 t of fresh meat with the highest production during 2003 valued at 8.4 million US$, (but most of the landing during the last few years is below the minimum legal size of 90 mm shell length). This extraordinarily value has resulted in intensive fishing operations and the fishery today faces a serious decline in stock density and availability of large individuals.

This study aims to assess the reasons for the decline, and provide information on the status of the fishery to develop a management plan. The study was carried out over two years including monthly sampling from three selected permanent stations: Mirbat, Hadbin and Sharbithat, following by an intensive survey along the whole coastline. It covers aspects of the ecology and dynamics of this fishery and presents information on the abalone distribution, abundance, morphometry and size composition structures, habitat, competitors, predators, commercial production and marketing, biochemical composition, environment parameters, preservation, genetics, biology including growth, reproduction, spawning season, sex distribution, maturity stages and size at first maturity.

The fishery is restricted to the southern coastline, which is strongly influenced by the monsoon winds, which result in major changes in the environmental conditions and the upwelling of deep-cold nutrient-rich water. This could regulate the limited distribution of this fishery between Ras Mirbat and Suqrah. They occurred at more exposed shores at depths up to 20 m, but most of the populations are found between 5-10 m. Abalone habitats were mostly destroyed and showed signs of degradation in algal cover. Sea urchin is the main competitor present at 25 times the number of abalone. Sea star also abundant and shows sign of predation on abalone. Abalone population density was 0.07 individuals/m^2, which is inadequate to support a good reproductive level and maintain a sustainable fishery. The remaining stock was calculated at 707000 pieces (54.5 t of flesh wet weight).

This fishery is regulated through a fishing season for two months a year combined with a MLS of 90 mm SL, but 50% of the divers catch is below this limit. Most of remain populations are of small and medium sizes. In addition, females are larger than males resulting in fishing selectivity; therefore, fewer females remain in the population, which has an impact on reproduction and recruitment.

The species sexually matured at sizes over 60 mm SL. Spawning occurs from November to March/April at all the three sites. Growth is faster in the first year and decrease with age. Fishing mortality is high and egg production very low. Populations of *Haliotis mariae* found in all the three study areas of Oman were genetically linked.

The *H. mariae* stock is considered seriously compromised and the remaining population seems unsustainable under current fishing pressure combined by environment destruction and other biological failures. Reduction of exploitation rate by 50%, increasing the size at capture, relocating the fishing season, adequate monitoring, controlling and surveillance with strong enforcement of existing legislation are necessary to conserve and protect the fishery. The resource user groups need to be involved in management process of this fishery and education programms and awareness campaign should be introduced to highlight the need for divers to change attitudes and practices to make the fishery more sustainable. Research and further studies on more aspects of this fishery are recommended.

ACKNOWLEDGMENTS

This study was undertaken as a recommended project in my M.Sc. dissertation to provide useful information about the Abalone fishery of the Sultanate of Oman.

Foremost, all praise and thanks be to Allah, who created me, helps me and has given me the health, ability and peace of mind, without which this thesis would be impossible to complete.

I would especially like to extend my sincere gratitude and appreciation to my supervisor, Prof. Ian G. Cowx, Director of Hull International Fisheries Institute, Hull University to whom I am deeply indebted for his constant encouragement, helpful guidance, endless advice and valuable comments throughout the period of this study. My gratitude is also due to my previous and recent second supervisors, Mr. Stephen Ridgway and Dr. Jonathan Harvey respectively, and to all the staff of HIFI for their assistance and kind help during my course, particularly Emma Doy.

I am very much indebted to The Islamic Development Bank (IDB) for awarding me the Merit Scholarship to undertake my Ph.D study and for the financial support received during the period of my scholarship.

This study was carried out with the support of Ministry of Agriculture and Fisheries (MAF), Oman, for whom I work, and funded through the Agriculture and Fisheries Development Fund (MAF). Without this funding and support, this study would not have been completed. This is an appropriate opportunity to record my thanks to my Government, represented by the Cultural Attache's Office-Embassy of The Sultanate of Oman-London, for giving me the opportunity to undergo this course and for financial support.

The huge task of sample collecting, measuring and data entering was conducted with the help of a project work team from Raysut Fisheries Research Laboratory (MAF) under my supervision. The sampling itself was conducted in an intensive period in sometimes very difficult conditions. I am thankful for the collaboration and hard work of all the Abalone Project Team; divers and members involved in the project, particularly Ali Rajab Al'Mashaiki, Salim Ahmed Al'Ghassani, Mohamed Abdulrahman Balkhair, Adel Ahmed Al'Shanfari, Salah Suliman Aubaid, Saeed Rabee Al'Shugaibi, Redha Saeed Khalfan, Sami Jaman Qsboob, Abdulla Ahmed Al'Ghaili, Roberto Indo Meguro, Tariq Abdullah Bahajaj and Kulihmo Basheer. Ali Al'Ghailli and Musalam Rafait from Raysut Fisheries Research Laboratory were particularly helpful.

I am also grateful to the participating abalone divers Musalam Zidan Jabob, Abubaker Abdullah Al'Saiari and Mohammed Mohsin Al'Mamari of the Mirbat Diving Centre accompanied the work team during the whole period of sampling visits. Other professional abalone divers (Awlaad Al'Garrmal; Shanfary divers) provided accommodation and help in collecting monthly samples for Sharbithat station during the rough sea. I appreciated the project members' patience with all the hardships and obstructions we faced during the different steps of the project.

Thanks are also extended to the following: Quality Control Centre (MAF) for undertaking the biochemical tests, which were conducted by Khamis & Aadel. Marine Science & Fisheries Centre (MAF) for providing the Hydrolab device used in the study. Dubai Advance Biotechnology Centre (UAE) for undertaking the DNA analysis. Management and staff of Raysut Fisheries Research Laboratory for their support and invaluable assistance with the project and in getting the information and data needed for this study. Directorate General of Agriculture and Fisheries (Dhofar) represented in the regional Agriculture & Fisheries Development Centres at Mirbat, Sadah and Shaleem for their cooperation. The Wali (local governors' office) and the Fisheries Committee (Sonnat Al'Bahar) at Mirbat, Sadah and Shaleem regions, for their cooperation and logistic support provided to the project team during the course of the fieldwork in the study areas located under their administration, which facilitated survey of the coast and increased the efficiency of the project.

Many thanks to the International Abalone Society members, particularly Scoresby Shepherd, Robert W. Day, Peter Cook, Roy Gordon, Roy Sasaki, Sergio A. Guzman Del Proo, Rodney D. Roberts, Robert J. Tara, Simizo Tosiatu, Hideki Takame and Joe Altick for their valuable and useful discussions during the 5th International Abalone Symposium, Qingdao, China, October 2003.

I wish to thank Kathryn Spry and an anonymous reviewer for their helpful editorial guidance, comments and assistance in correcting the English grammar in this work. I would like also to thank Mr. Mohammed Ahmed and an anonymous critic, who offered me their help and assistance with statistical analysis. My gratitude also goes to all my friends and colleagues in Oman and here at Hull who encouraged and supported me in my study, personal life and career. My gratitude is due to my housemate in Hull, Moawiya Al'Rawas, for his kindness, help and support during my stay. It is also due to Majed Al'Moalla for his assistance with maps preparation.

Finally, I wish to record my sincere appreciation of the love, sacrifices and unlimited help and support particularly of my parents, my mother Mohani and my late father Salim, and of everyone in my family, who in one way or another encouraged me to study and overcome all obstacles and who always pray and worship God for my success. I am deeply indebted to my wife Fatma and our daughter Bayan, for their understanding and patience, especially during the long periods I had to be away from the family, both in the course of fieldwork and while at the University of Hull writing up this thesis.

DEDICATION

This thesis is dedicated to the memory of my Father, the late Salim Ali Mohsin. His love for education always inspired me to aim higher. May Allah, in his mercy, forgive him and accept him in Paradise. It is also dedicated to my wife and our daughter Bayan.

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CHAPTER 1

INTRODUCTION

1.1 General Background

The Sultanate of Oman is situated at the southeastern corner of the Arabian Peninsula, between latitudes 16° 40' and 26° 20' North and longitudes 51° 50' and 59° 40' East. It encompasses an area of 309,500 km², and the population is about 2.3 million. Oman, with a 1700 km-long coastline extending from the Straits of Hormuz at the entrance of the Gulf in the north to Dhofar at the border with the Yemen Republic in the south, overlooks three different bodies of sea: the Arabian Gulf lies off the western shore of Musandam Peninsula; the Gulf of Oman forms the northeastern coast; and the Arabian Sea borders the long southern and central coast (Figure 1.1).

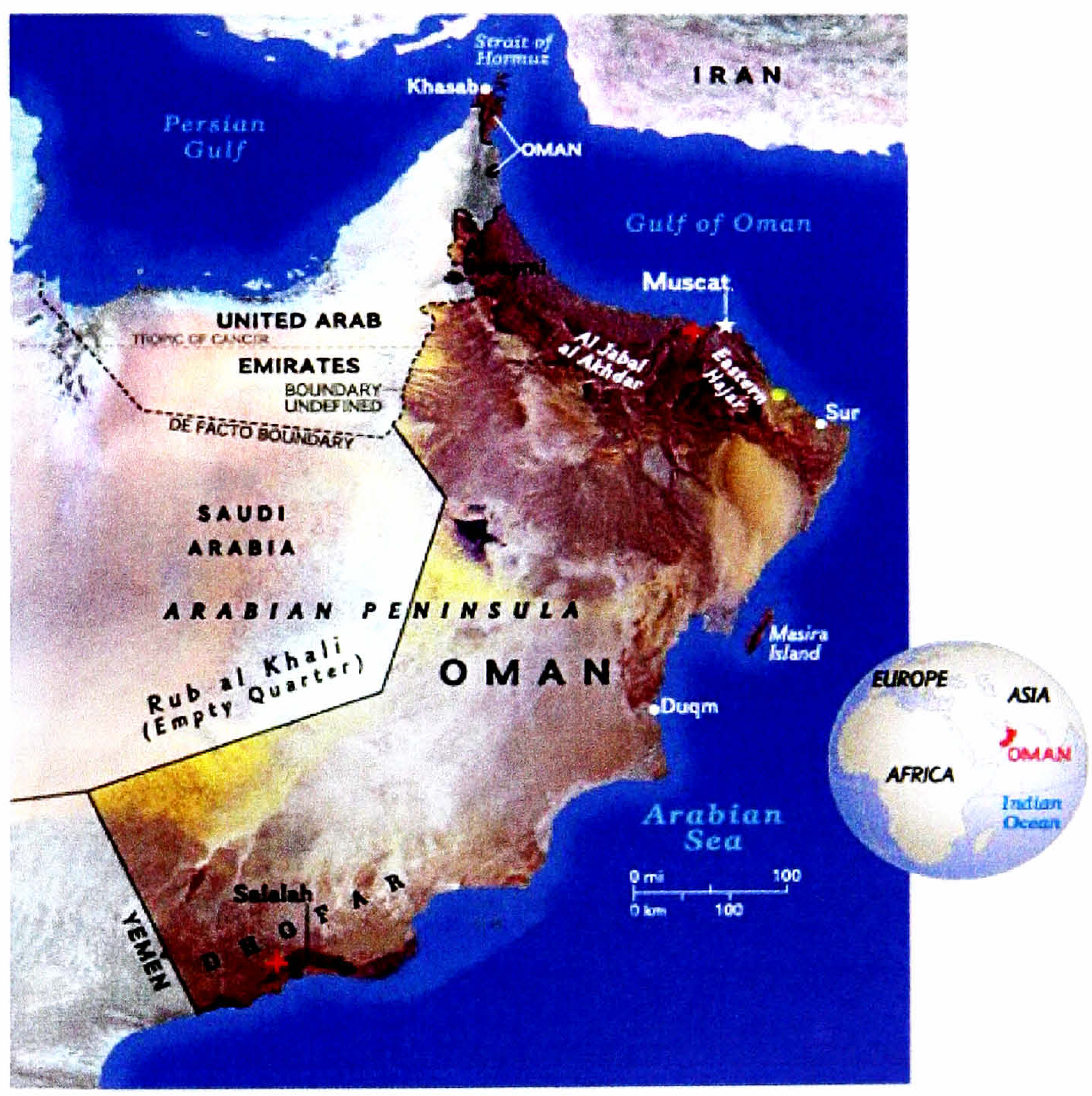


Figure 1.1 Map of Oman (showing the country location)

A 200- mile exclusive economic zone extends seaward from the shores (Ministry of Information 2004). Oman has about 340,000 km² of inshore and offshore waters which contain extremely rich fishing grounds, the potential of which has yet to be evaluated fully. The country's economy depends mainly on oil as a source of income. However, fisheries are a valuable adjunct to this source and considered as the second economic contributor, as they provide employment opportunities, revenue and nutrition for a large portion of the population (Ministry of Information 2005). For centuries there have been small and often isolated fishing communities along its coastline. In the 1970s, there was a drift by young men away from these communities to the main cities, where they could get better jobs in the government or even the private sectors. Many urgent steps were taken by the Government to stem this drift. The Fisheries Department, formed in 1972, became a Directorate General in 1974, and this was later absorbed into the Ministry of Agriculture and Fisheries, which is concerned with the development and the administration of this sector. The introduction of the Fishermen's Encouragement Fund in the 1978 was most effective in encouraging the fishermen to continue with their occupation. Subsidies and financial assistance were given for the purchase of fibreglass fishing boats, outboard engines, fishing gears, and cooler trucks (Ministry of National Economy, 2003; Ministry of Information, 2005).

Over the last 35 years great effort and much progress has been made by the Government to expand and modernize this traditional industry, to develop the fisheries to full productivity and exploit their potential. Many fishing harbours were constructed along the coastline to enable fishermen to berth their boats more conveniently and to operate even during rough weather. These harbours were provided with cold-storage and processing facilities, technical support, such as maintenance of fishing gears, and servicing of outboard engines through Ministry marine workshops. This is to encourage the fishermen to land their catch at one point, making it easier to monitor the landings. Moreover, many fish companies were established for external and internal marketing of traditional products. Such procedures have resulted in the increased availability of important facilities to accommodate and market fisheries production at high prices and increase exports and income from these resources. Large-scale commercial fishing companies were also established and they have played their part in the development of the fishing industry.

The Ministry of Agriculture and Fisheries has taken a number of steps to conserve the resource while at the same time developing commercial fishing and preserving the livelihoods of traditional fishermen. The activities of the fisheries sector are controlled under the Marine Fishing and Living Aquatic Resource Law, issued by the Royal Decree No. 53/81, and the Executive Regulations of the Law, issued in accordance with the Ministerial Decisions No. 3/82 and 4/94. These include restricting the fishing for lobster *Panulirus homarus* and abalone *Haliotis mariae* to two months a year with a minimum legal size, regulating the size of nets and equipment used for fishing, as well as defining the areas, depths, quantities and kind of fish that may be caught commercially. These regulations are designed to protect the traditional fishing industry. Inspectors, assisted by the Royal Air Force of Oman and Royal Oman Police coastal patrols, monitor commercial fishing vessels. Commercial fishing is limited to 15% of the total catch and within Oman's territorial waters; foreign vessels may not fish without a licence.

The total landing of the whole fisheries sector rose sharply through the 1980s, reaching a peak in 1988, after which there was a decline (Ministry of Agriculture and Fisheries, 2003). Research carried out by the Ministry of Agriculture and Fisheries indicated that over-fishing has had a major part to play in this decline. As a result, restrictions were imposed on the fishing of certain species, such as lobsters and abalone, of which there was a noticeable decline in stocks. This study is being undertaken to provide much needed information about different aspects of the abalone stock status and to establish the causes of this decline. More research has been directed to other species, including studies of different stocks and the future development and management of the vast range of marine species to be found in Omani waters, in addition to a more academic role in the general ecology of the marine environment, with particular emphasis on the conservation of ecosystems and endangered species such as abalone (Ministry of Agriculture and Fisheries, 2003). The results of these studies will assist in formulating policies and evolving plans for their efficient management.

1.2 Abalone Resource

The abalone (*Haliotis mariae* Wood, 1828), which is locally called *Sufailah*, is a marine herbivorous gastropod mollusc belonging to the genus *Haliotis*. They live attached by their large and well-developed muscular foot to the rocks at the intertidal and subtidal zones. The foot muscle is also used for locomotion in the form of slow gliding motions over the substrate. This species is considered to be by far the most valuable export commodity and has the highest economic yield per kilogram among the seafood produced in Oman (Al-Hafidh, 1999). *Haliotis* species are not restricted to Oman. They are found world-wide, and known species of abalone are inhabiting temperate and semi tropical coasts. Approximately 75 abalone species have been recorded around the world (Lindberg, 1992). Only 20 of them, however, are relatively large and captured for commercial fisheries (Uki, 1989). They are commercially exploited for their valuable meat and shell. Abalone forms a major fishery in some countries such as Australia, South Africa, Mexico, Japan, United States, New Zealand, Korea, Taiwan, Philippines, China, Chile, France and Thailand, which benefit from the great demand and their high price on international markets (Shepherd *et al.,* 1992). The current world harvest of abalone is not known. In 2002 the harvest of identified abalone species from all sources (fisheries landing, illegal catch, and cultured production) was 22677 t (Gordon & Cook, 2004), but in some countries abalone is not singled out but grouped within the harvest of unidentified gastropods. Large-scale exploitation of this group has resulted in the depletion of wild stocks. Therefore, the worldwide harvest of abalone has been declining for decades (Nash, 1991; Officer *et al.*, 2001; Gordon & Cook, 2004). Moreover, many abalone fisheries have collapsed, and it is likely that the remaining abalone stocks will be put under greater pressure (Gordon & Cook, 2004). The reasons behind stock collapses are varied, but they may be linked to excessive fishing pressure on the resource, inappropriate management regimes, inadequate enforcement policies, pollution, natural recruitment failure, habitat loss and disease.

In Oman, *Haliotis mariae* is considered to be an endemic species (Johnson *et al.*, 1992) restricted to Oman's coastal waters of the Arabian Sea (Stirn & Al-Hashmi, 1996) and it is the only *Haliotis* species occurring in Omani waters. It inhabits a short rocky coastal zone of about 200-250 km in length between Mirbat and Sharbithat, and in the vicinity of Soqrah and some islands in the southern region of the country. This region comprises one-third of the total area of Oman and has the longest coastline, about 600 km, facing the Arabian Sea (**see** Figure 3.1 Chapter 3).

This fishery is a means of livelihood and an important source of income for the people who live along the coastline between Mirbat and Sharbithat, as well as for new divers from the internal regions who have recently entered this field.
Due to huge demand from the East Asian market and the extraordinarily high price for this product, commercial abalone exploitation has steadily increased since the 1970s (Johnson *et al.*, 1992) to reach an annual production of about 50.5 t of fresh meat in 1988, valued at O.R. 1.062 million (US$ 2.758 million). The production level then decreased in quantity and the landings for 1989 were 42 t, increasing to 44 t in 1990.

Although the fishing season in 1991 was reduced from six months to two months and a minimum legal size (MLS) of 90 mm shell length (SL) was introduced to protect the resource, the production was around the same level, 42 t, because of the increasing effort of the divers during the two months. Subsequently, although the price continued to increase, production started to decline and fluctuated to reach 39 t in the 1997, valued at O.R. 2.7 million (US$ 7.13 million), but declining to 32 t in 1998, and in the following year it declined sharply to the lowest level in the fishery's history, around 29 t valued at only O.R. 1.7 million (US$ 4.415 million) (Dept. of Fisheries Statistics, 1990-1999).

Although the catch of this species accounts for only a small proportion of the whole production of the fisheries sector in Oman (about 0.03% of the sector landings), because of its high value, its contribution to the sector is important compared with other species and it accounts for 6% of the whole fisheries sector income. The price of abalone reached its highest level in 1997 at O.R. 68 (US$ 177) for a kilogramme of fresh meat.

As a result of the intensive fishing operation for this species, combined with lack of attention to the status of the stock and breaches of the rules, many problems have started to occur, such as over-fishing; catching small, immature specimens, which leaves few sexually mature abalone to breed; overturning the boulders which are the preferred habitat for settlement by larval abalone and so destroying the habitat; and diving out of season which has an effect on the spawning season. In addition to these problems, there are other problems due to environmental changes and to the role of nature. The stock is continuing to decline and the abalone fishery is in danger of collapse if proper care is not paid to conserving it and if no immediate and active action is taken. The continued high demand for abalone requires careful management of the fishery to ensure the breeding stock is not endangered.

1.3 Justification for the Study

As has been illustrated above, abalone is important as a valuable marine product of Oman, but the prevalence of many problems is starting to threaten the sustainability of this fishery. However, there is a lack of information and studies on this resource, as only a few studies have been carried out in Oman, and so far there has been no comprehensive study on this species to provide the Fisheries Department with necessary scientific and biological information about the resource which can be used in the conservation of the stock so that it should remain sustainable. It was therefore, necessary to undertake a full research programme on the status of this fishery.

1.4 Aims and Objectives

This study aims to investigate the status of the resource and to understand the dynamics of the fishery. It seeks to achieve the following:

- To review and evaluate the current status of the abalone fishery in Oman;
- To ascertain possible causes of depletion;
- To formulate a sound management policy to conserve the abalone fishery;
- To provide opportunities to add value to production;
- To provide a reliable biological, ecological, environmental, biochemical, and genetically basis and gain an understanding of the fishery for management purpose in order to conserve the resource base, protect the resource from extinction, improve the stock and create a sustainable fishery.

1.5 Research Approach and Schedule of the Study

The research was conducted in two phases.

Phase one: Monthly sampling from three permanent stations at the main landing sites (Mirbat, Hadbin and Sharbithat) for a period of 24 months between April 2003 and March 2005. This phase included all the environmental, biological, ecological, biochemical and preservation aspects of the fishery. It also included sampling the divers' landings during the 2003 fishing season, collecting samples from the three areas for genetic studies and a mark & recapture experiment.

Phase two: A complete and intensive diving survey took place along the whole coastline between Mirbat and Sharbithat between March 23 and April 25 2005. This included distribution, abundance, stock estimation, habitat, algal communities, environmental effects, and associated animals (competitors and predators). In addition to the above mentioned field work, the Fisheries Department's available abalone data were reviewed, and all previous studies and reports on *Haliotis mariae* were consulted (Waleed Associates, 1981; Sanders, 1982; Bosch & Bosch, 1982; Anon, 1984; Barratt *et al.*, 1986; Savidge *et al.*, 1986, 1988; Bouhlel, 1989; Shepherd & Johnson, 1991; Johnson & Shepherd, 1992; Johnson *et al.*, 1992; Siddeek & Johnson, 1993; Shepherd *et al.*, 1995*a*, 1995*b*; Stirn & Al-Hashmi, 1996; Ogawa, 1994, 1997; Al-Hafidh, 1999; Iwao, 2000; and Roperto Endo *et al.*, 2003 in press).

1.6 Structure of the Thesis

This thesis examines the current status and different aspects of abalone fishery in Oman and covers the factors that appear to be responsible to threaten this resource. It comprises seven chapters, including this introductory chapter. This chapter **(Chapter One)** presents the Sultanate of Oman location and provides a general review of the fisheries sector with special reference to the abalone fisheries. It discusses the development and importance of the fisheries sector to the Omani economy, and the current fisheries regulating approach, as well as the problems and justification leading to the need for this study. It also identifies the aims and objectives of the study as well as the research approach.

The remaining chapters are organized as follows: **Chapter Two** identifies the study species and describes its life cycle. It also reviews and highlights the history of abalone fishery in Oman and describes the fishing operations and methods. It explains the monitoring of stocks and landings as well as the data collection systems. It provides information on the production and value of the fishery and discusses their trends. Information is also given on marketing, pricing of abalone and divers' revenues. This chapter also provides a background on aquaculture attempts and prospects for stock enhancement, and discusses the socio-economic considerations of this fishery.

Chapter Three presents a two-year field study conducted on a monthly sampling basis. It describes the study area and sites and explains the materials and methods used to investigate the current status of the fishery, and examines the influence of environmental parameters. It is also examines the divers' catch during the fishing season. It explores different aspects of the fishery biology and describes the population characteristics, including the morphometry, size composition, sex ratio, spawning season, maturity stages and sex at first maturity. It presents a mark and recapture experiment to estimate the growth rate. It is also quantifies the biochemical composition of abalone flesh, and estimates the weight losses during the preservation process.

Chapter Four presents the results of an intensive survey carried out along the whole coastline of the fishery range, covering its distribution, abundance and stock estimation, habitat, competition, and predators. It also discusses the effects of the monsoon on coastal waters and environment and their impact on abalone populations.

Chapter Five investigates the genetic divergence of *Haliotis mariae* at three selected sites. It explores the similarity and deference between the populations among the sites and compares it with other species world-wide.

Chapter Six highlights fisheries management issues and examines the management system used in Oman. It outlines the defects in abalone fisheries management and integrates the outputs of the above chapters in a discussion of management initiatives that ought to be undertaken to ensure long-term sustainable fisheries.

In Chapter Seven, the researcher presents a conclusion and recommendations, as well as suggestions for further research.

CHAPTER 2
ABALONE FISHERY

2.1 Introduction

Abalone (*Sufailah*), *Haliotis mariae* is an herbivorous grazing gastropod that belongs to Archaeogastropoda, Prosobrancia of the family Haliotidae (Hayward, 1996). This species is a common inhabitant of rocky intertidal and subtidal zones of the southern coast of Oman between Mirbat and Sharbithat. It lives attached to the rocks by its large and well-developed musular foot. The foot muscle is also used for locomotion in the form of slow gliding motions over the substrate. They feed on small red and brown algae. It is the most valuable species among the dive fisheries and has therefore been a target for commercial fishing. *Haliotis* species generally, reaches maturity at about 3-4 years of age and they can live for 15-20 years in temperate waters, although *Haliotis mariae* probably live for less than 10 years (Shepherd & Johnson, 1991).

2.1.1 Abalone life cycle

The life history of the Omani abalone (*Haliotis mariae*) is poorly known, and the life cycle of this species is significantly different than for other Haliotis species (Stirn & Al-Hashmi, 1996). Generally the sexes are distinct and easy to distinguish when the gonads begin to develop, in response to sea temperatures changes and seasonal availability of macroalgae which are considered as the main food source. These animals are broadcast spawners, that is, they release their gametes (sperm and eggs) into the water column where they meet and fertilization occurs. Broadcast spawning usually occurs when all the mature male and female abalone in the area congregate in the shallow subtidal water, gathering in relative high densities on the top of highest rocks or sometimes balanced on top of one another, up to six abalone high, in order to be higher when sperm is released, which gives a great chance of successful fertilization.

When the sperm are released through the pores with the respiratory current, the nearby females are induced to spawn. The presence of eggs and sperm in the water may stimulate other abalone to spawn, thus increasing the chances of fertilization (California Abalone, Web Site). *Haliotis mariae* shows early reproductive maturity at the age of one year, which is different from other Haliotidae spp. Newly mature juveniles produce between 400,000 and 800,000 eggs (Stirn & Al-Hashmi, 1996), while a large female may lay up to six million eggs (Johnson & Shepherd, 1992). The ejected eggs of *Haliotis mariae* form a mucous monolayer attached to the substratum, whereas other abalone species produce pelagic eggs (Stirn and Al-Hashmi, 1996). Within one day after the fertilization, the eggs are hatched as microscopic free-swimming trochophore larvae, which feed on there yolk sacs. The trochophore larvae move upwards in the water column, attracted to light, and drift with the current in the shallow coastal waters. These small larvae only last about one day before they grow a minute shell and develop into the second stage of larval life as veliger larvae. Within 4 to 8 days of hatch, the larva undergoes metamorphosis, turning into a very small juvenile abalone (Figure 2.1). These small abalones start to move on the coralline algae and crevices in the reefs, searching for microscopic algae and tiny diatoms which are present on the substrate. As they grow, they move to the deeper section of the reef (King, 1995). These small abalone may grow to adulthood if a suitable habitat is located. The chance for an individual larva to reach adulthood is very low. Although abalone and other molluscs are prolific spawners, the mortality rate is very high and probably exceeds 99% (California Abalone Web Site).

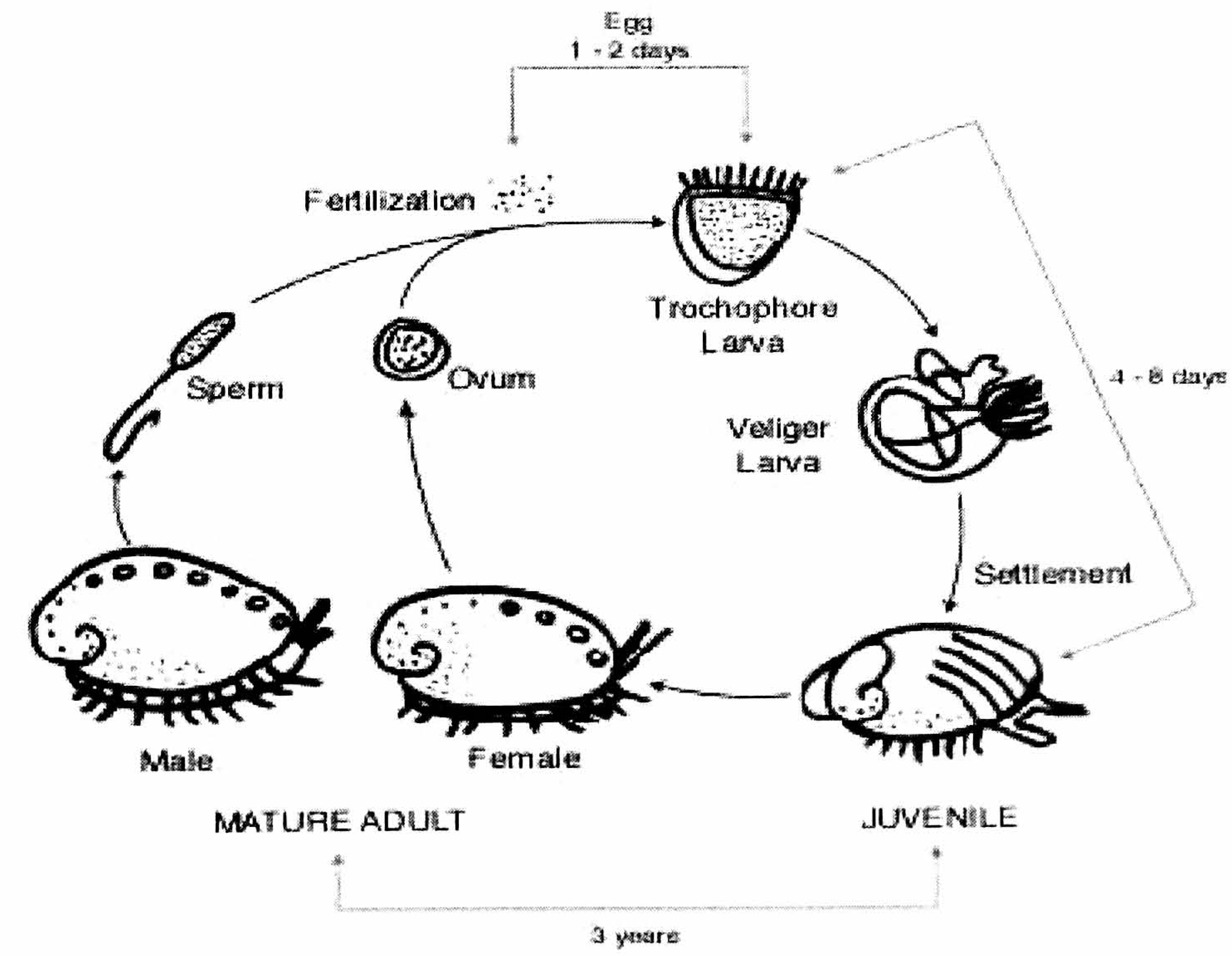


Figure 2.1 Abalone life cycle (Source: Spruce Roots Magazine Web Site)

2.2 History of the Fishery

Abalone has been fished in Oman for many years, and the early history of the fishery is unknown. Johnson & Shepherd (1992) indicated that during the 1950s and 1960s, the Omani abalone were boiled and sun dried, and taken to Hadramaut in the Yemen, where they were exported to the Orient. After 1965, the abalone were sent to Dubai in the U.A.E. then exported through a middleman to the Far East. The modern fishery began just after 1970 when the demand for abalone from the South East Asian market increased and the price started to rise. At the beginning of the 1980s, some abalone traders started to export their products directly to the Hong Kong market, a practice which continues today. Also, some groups of abalone divers began to sell their harvest directly to the Hong Kong market. The fishery was initially restricted to the coastal areas between Mirbat and Sharbithat and perhaps around some islands in the Dhofar region. This type of sea food was an important source of traditional diet of coastal village residents and a main source of income. However, the abalone shells were discarded due to their low value and lack of market.

2.3 Fishing Operations and Methods

The present abalone fishing season is only for two months a year (from 15 October to 15 December). The fishery began with shore pickers who later turned to diving. The modern abalone fishery is made up of divers working the deeper waters and operating from fibreglass boats with high-power outboard engines to enable them to reach the deep water fishing grounds. These groups start either from small harbours, as in Sadh or Hadbin, or from the sea shore, as in Foshi and Sharbithat.

Other groups are distributed along the coastline, around the shallow rocky areas. They operate independently or sometimes in groups of two or more, using a variety of entry points, usually starting from shore in the coves around the diving camps. They wade into the water from the shore and swim out to the deeper water around the rocks. Some of these groups use four-wheel drive vehicles to gain access to remote sheltered gullies. Although the coastline extends to about 250 km, not all of this is fished, due to unsuitable areas (sandy shores) or lack of available abalone grounds.

The women and the non-diving people, such as the elderly and recreational fishers, operate in the shallow waters as shore pickers looking for abalone in rocky areas during low tides. This group have recently faced competition from younger people, mainly school students who are truanting from school to dive.

The divers usually use a special tool like a big screwdriver to lever the abalone from the rock. This tool has rounded edges, which makes removing the abalone much easyer. They collect the abalone in open mesh bags tied to their waist. Only skin diving is permitted, and the diving should be at depths of more than 8 metres; but this is ignored by most of the divers. The use of any artificial diving gear such as scuba or hookah for abalone fishing is strictly prohibited. This rule was introduced to restrict access to the abalone population. The divers are only allowed use snorkel, fins, and rubber diving suits.

The diving day normally consists of numerous short dives with a combined duration between 4-6 hours. Usually the divers stop diving at prayer due time and return to the shore or to the diving camps to perform their prayers and to have their meal or rest; they continue thereafter. At the end of the fishing day, the divers return to the diving camps with their harvest and start removing the flesh from the shells, mostly by hand with a knife. Then they sell the flesh according to weight to the abalone traders in the collecting centres.

Diving time during the fishing season is affected by the weather and sea conditions, due to the monsoon wind. In addition, it is affected by social events in the area, such as weddings, deaths, national events and celebrations, as well as the daily price of abalone. Usually the divers only operate when the sea conditions are at their mildest. On a number of days during the season, especially in the second month, windy weather makes diving difficult, forcing the divers to stop working or even to leave the camps.

2.4 Monitoring Stock and Landings

Abalone fishing in Oman takes place in the southern region, at the fishing sites between Mirbat and Sharbithat. Fishery monitoring and record-keeping involves the Department of Fisheries logbooks, landing site visits and export permission certificates. These forms of monitoring, integrated with research programmes involving the collection and analysis of data collected from the divers through interviews and from landings and research biological sampling, are used to provide management advice, which is, in turn, used to guide legislation. This system is not working well for the abalone fishery, because the data collection system has failed to provide reliable data. In addition, this species is restricted to a short and difficult topographical coastline in a remote area where data collection is problematic.

Today this fishery is on the edge of collapse, despite the fishing season being reduced several times from six months to two months per year since 1991. The landings have continued to decline during the last few years, mainly due to over-exploitation. Today most of the landings are of small sized specimens below 90 mm SL, which indicates the serious situation of the resource, which could be considered in danger. Despite the inspection visits by the Department of Fisheries inspectors during and after the fishing season to protect the resource against the rule breakers, the problems persist with over-exploitation of this valuable resource.

2.5 Data Collection System

The Ministry of Agriculture and Fisheries, in order to control the abalone fishery in Oman and to obtain essential information and statistical data for the purpose of management, supplies the abalone traders with logbooks, and requires them to complete them during the fishing season. They are collected by the Department staff at end of the season. Abalone fishery statistics reports are based on these data submitted by the abalone traders during each fishing season.

Data concerning each diver's landings are recorded in the logbook by the abalone trader. The reported data are reviewed by the Department of Fisheries officers through daily visits and used as a record to monitor the landing and the stock.

This logbook is a simple monitoring tool used to provide the basic catch records about the fishery in the landing sites. The trader must provide data concerning the catch weight landed by each diver, price paid to the diver, fishing site, plus other information about diving days, and number of divers selling to them.

The data collection depends largely on the cooperative efforts of the abalone traders, divers, and Department personnel responsible for the logbook monitoring and checking who have, through their effort, provided the statistical data available for this study.

Although the traders have the opportunity to export their product during or after the season, they must get export permission from the Department of Fisheries. The amount exported by each trader is reduced from his total stock recorded at the Department of Fisheries after an inspection visit. If the abalone remains unsold after the season and before the start of the next season, then the trader should inform the Department of Fisheries about the quantity remaining. These data are of significance to the Ministry of Agriculture and Fisheries in the monitoring system and in the management of the abalone resource for wise utilization.

2.6 Production and Value

Most of the production during the last few years has been of small and medium specimens, reflecting the increasing effort and the decline in the availability of large abalone population. In 1988, the average catch per day per diver was about 2.11 kg; in 2003, despite increasing the diving hours and using new devices and skills it was around 2.04 kg and mostly of small specimens (Table 2.1). According to Johnson & Shepherd (1992), about 10 to 20 years ago, the divers regularly took between 300 to 400 abalone a day, almost all of a large size, in the shallow water around Sadah. The situation today, however, is totally changed, due to the increasing number of divers from 244 in 1988 to 951 in 2003, besides the decline in the stock and the unavailability of large size abalone.

The total catch peaked in 2003 when 56.6 t were landed, but about 50% of the catch during this season was below the legal size (< 90 mm shell length). A peak was also seen in 1988 when 50.5 t were landed. There may have been further peaks prior to 1988, but catch data are unreliable. Harvest fluctuated considerably between 1988 and 2003 below 56.6 t in 2003 and less than 30 t in 1998. Production realised during the 1989/90 indicates a decrease compared with those for 1990/91 and 1991, but it is more than those of 1993 and 1994, when it was estimated as between 34 t during 1993 and 36 t during 1994, which is lower than the production of 2003 at 56.6 t (Figure 2.2) (Dep. of Fisheries Statistics, 2003).

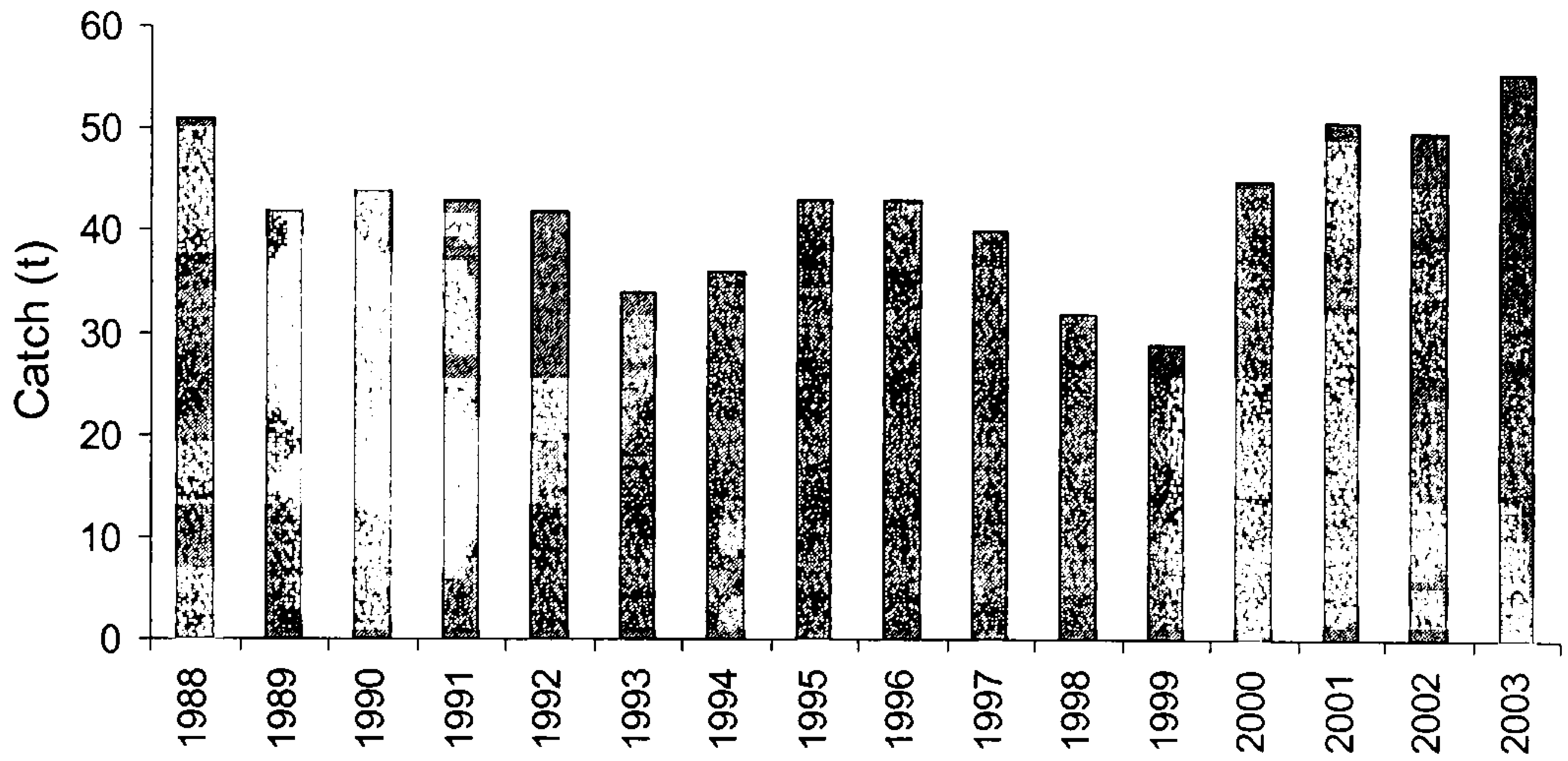


Figure 2.2 Abalone production during 1988-2003

The fluctuated decline in the landing is due to the decline in the stock for several reasons, including increase in the price, increase in the number of divers, introducing the speedboat, using flippers, reduced access and fishing time in the lobster fisheries, the high demand and acceptance of *Haliotis mariae* into the Asian market, destruction of the abalone habitat through wrong fishing practices, breaking the law by catching and landing the small abalone and fishing out of season, and some environmental changes (see Chapter 3).

The study of the production distribution and fishing effort indicates that catch is relatively high at the beginning of the season but declines as the season progresses. For example, in the 2000 fishing season, 31461 kg were caught in the first month of the season but the catch dropped to 13019 kg in second month. This may be due to lower availability of abalone.

The productivity by fisherman in 2000 reaches 3.79 kg. per day at the beginning, and an average of 3.02 kg. per day during the whole season. Productivity has decreased and fluctuated during the last three years, and in 2003 it was 3.07 kg. per day at the beginning and decreased to 1.01 kg. at the end of the season, with an average of 2.04 per day during the whole season (Table 2.1).

Table 2.1: abalone catch (kg), value (× 1000 O.R.), average price O.R/kg, effort (number of divers, average number of fishing days/diver (** total N.F. days), and catch per day per diver) and diver's revenue between 1988 – 2003.

Year		Catch (kg)	Value (X 1000 O.R.)	Average Price (O.R.)	Number of Divers	Average N.F. days/diver	Catch/day/diver (kg)	Diver's Revenue (OR)
1988/89	Oct	9930	209	21	236	15	2.80	886
	Nov	11338	238	21	246	20	2.30	967
	Dec	8976	188	21	281	16	2.00	669
	Jan	7234	152	21	329	20	1.10	462
	Feb	10087	212	21	266	14	2.90	797
	Mar	3000	63	21	109	17	1.60	578
	Total	**50565**	**1062**	**21**	**244**	**** 25113**	**2.11**	**4359**
1989/90	Oct	10536	221	21	376	14	2.00	588
	Nov	9164	202	22	321	15	1.90	629
	Dec	6218	137	22	345	12	1.50	397
	Jan	7271	182	25	240	20	1.50	758
	Feb	4805	120	25	220	14	1.60	545
	Mar	3870	101	26	186	17	1.20	543
	Total	**41864**	**963**	**24**	**281**	**** 25261**	**1.60**	**3460**
1990/91	Oct	14889	387	26	325	22	2.10	1191
	Nov	12354	334	27	299	20	2.10	1117
	Dec	9551	267	28	284	20	1.70	940
	Jan	4254	123	29	488	7	1.20	252
	Feb	2919	82	28	208	10	1.40	394
	Mar	266	8	29	57	5	0.90	140
	Total	**44233**	**1201**	**28**	**277**	**** 24591**	**1.60**	**4034**
1991*	Nov	20990	756	36	882	12	1.97	857
	Dec	22064	794	36	798	15	1.84	995
	Total	**43054**	**1550**	**36**	**840**	**22554**	**1.90**	**1852**
1992	Nov	28676	1434	50	1000	15	1.96	1434
	Dec	12968	648	50	692	14	1.30	936
	Total	**41644**	**2082**	**50**	**846**	**** 24688**	**1.63**	**2370**
1993	Nov	26896	1076	40	991	11	2.40	1086
	Dec	7158	286	40	459	12	1.30	623
	Total	**34054**	**1362**	**40**	**725**	**** 16409**	**1.85**	**1709**
1994	Nov	25109	1004	40	1014	10	2.40	990
	Dec	11029	496	45	705	10	1.60	704
	Total	**36138**	**1500**	**43**	**860**	**** 17190**	**2.00**	**1694**
1995	Nov	32625	1435	44	1267	12	2.10	1133
	Dec	9880	435	44	710	13	1.10	612
	Total	**42505**	**1870**	**44**	**989**	**** 24434**	**1.60**	**1745**
1996	Nov	32638	1469	45	991	15	2.30	1482
	Dec	10040	452	45	590	16	1.60	766
	Total	**42679**	**1921**	**45**	**791**	**** 24305**	**1.95**	**2248**
1997	Nov	29721	2021	68	1069	13	2.19	1891
	Dec	10018	681	68	626	14	1.18	1088
	Total	**39739**	**2702**	**68**	**848**	**** 22661**	**1.69**	**2979**
1998**	Oct	18849	1018	54	1050	10	1.85	969
	Nov	11192	592	53	761	13	1.16	778
	Dec	1654	94	57	377	6	0.75	250
	Total	**31695**	**1704**	**55**	**729**	**** 22655**	**1.25**	**1997**
1999	Oct	20566	1021	50	876	9	2.48	1166
	Nov	7731	392	51	569	10	1.33	689
	Dec	385	21	54	80	3	1.51	260
	Total	**28682**	**1434**	**51**	**508**	**** 13814**	**1.77**	**2115**
2000	Oct	31461	1597	51	1439	8	3.79	1109
	Nov	13019	653	50	899	10	2.24	726
	Total	**44480**	**2249**	**50**	**1169**	**** 20502**	**3.02**	**1835**
2001	Oct	40175	1960	49	1376	11	2.75	1424
	Nov	10675	517	48	936	7	1.54	553
	Dec	4	0.175	50	3	1	1.17	58
	Total	**50853**	**2477**	**49**	**772**	**** 21691**	**1.82**	**2035**
2002	Oct	47103	2470	52	1624	15	1.96	1521
	Nov	2400	127	53	424	3	2.06	298
	Total	**49504**	**2597**	**52**	**1024**	**** 25632**	**2.01**	**1819**
2003	Oct	52546	2866	55	1467	12	3.07	1954
	Nov	3833	211	55	436	9	1.01	483
	Total	**56379**	**3076**	**55**	**951**	**** 21528**	**2.04**	**1819**

The more accessible fishing grounds have shown signs of excessive fishing pressure, whereas remote grounds showed less pressure but with better mean size. The largest fishery in 2002 was in Sadah and Hadbin, with harvests of 21843 kg and 14273 kg. respectively, while the lowest was in Sharbithat, Mirbat and Foshi, with 437 kg., 4604 kg., 8348 kg respectively (Figure 2.3) (Dep. of Fisheries Statistics, 2003).

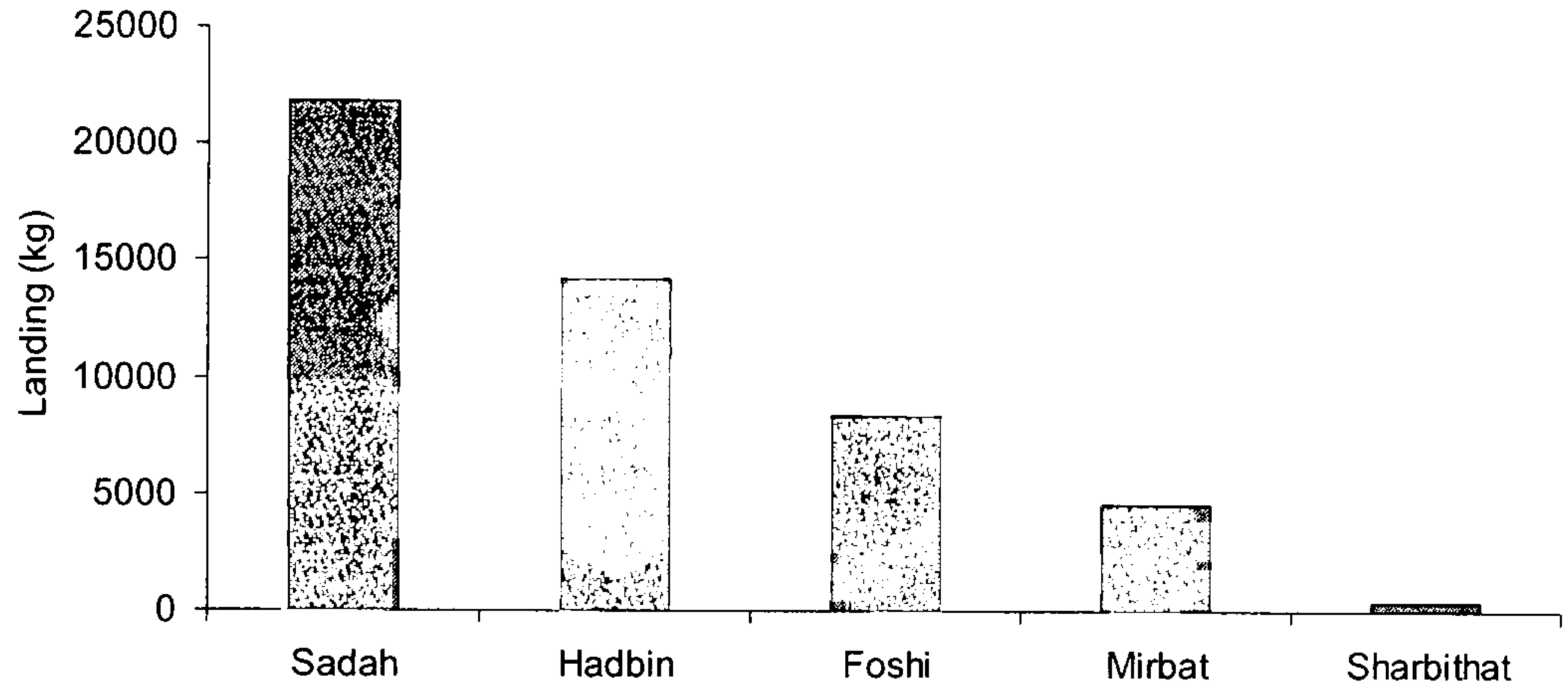


Figure 2.3 Abalone landing in different areas during 2002

The total value of the abalone landed increased considerably from about 1,434,000 in 1999 to 3,076,000 Omani Riyals in 2003. The highest values in the history of the fishery were about 3.08 million and 2.7 million Omani Riyals (US$ 8.4 million and US$ 7 million) in 2003 and 1997 respectively (Figure 2.4) (Dep. of Fisheries Statistics, 2003).

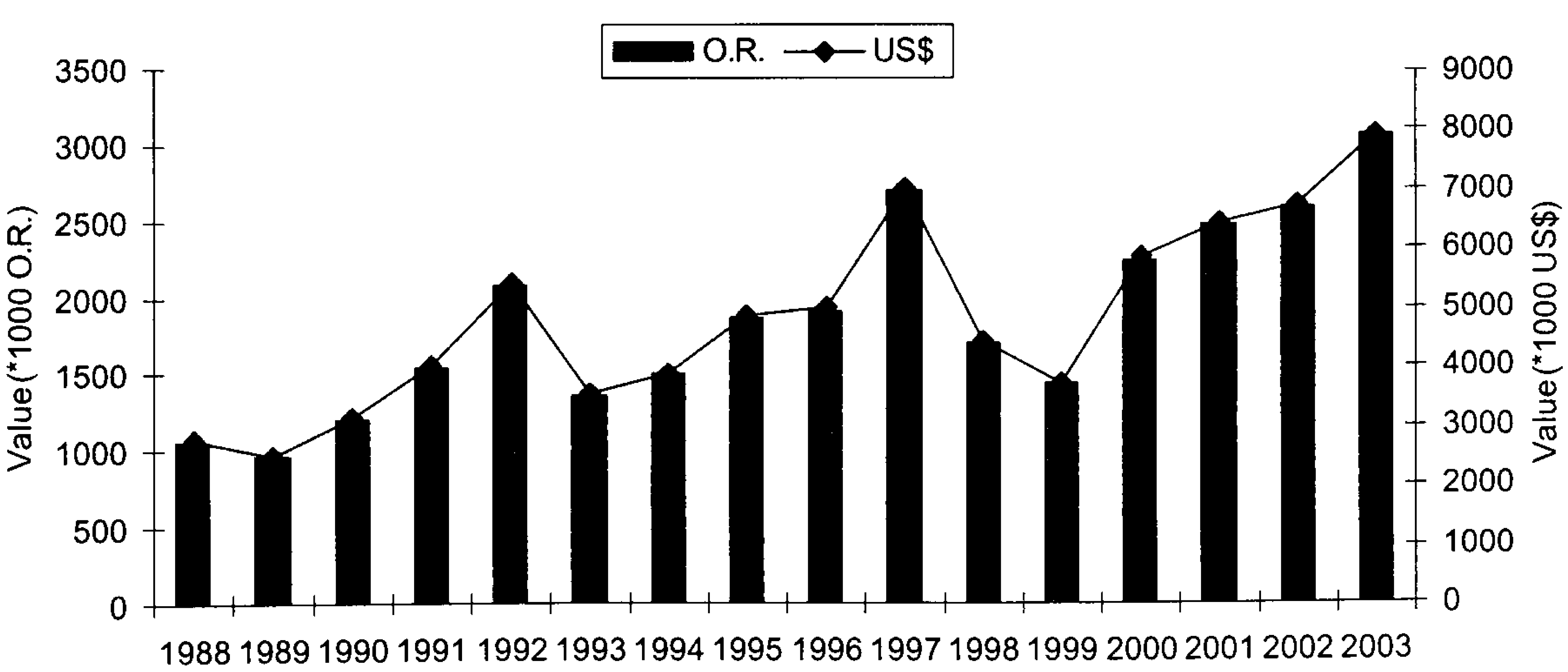


Figure 2.4 Abalone landing value in Omani Rials & US$ calculated on local first sale price basis during 1988-2003

Despite the heavy fishing during the last ten years, the fluctuation and unexpected continued production of this fishery may be due to the special characteristic of *Haliotis mariae,* which have been suggested to spawn in the first year, unlike other species (Stirn & Al-Hashmi, 1996).

2.7 Marketing, Pricing and Divers' Revenues

Specific abalone traders handle the marketing of most of the abalone landed and control the first sale price given to the divers. Many divers sell their catch freely to the abalone traders, but some of them are obligated to sell their catch to a particular trader because of a previous arrangement or contract. Abalone traders may sell product in whatever form they wish and to any market, although the abalone production has traditionally been exported only in dried form. There have been a few attempts by some local fisheries companies to export live abalone during or out of season, but this is an experimental approach and is done only on a small scale.

The divers usually sell their catch to the traders at the collecting centres and the price paid to them varies slightly throughout the year depending on the method of sale. There are two methods, some of the divers prefer to sell for cash and they get their money directly after their catch has been weighed, depending on that day's price. Others only register their name and the amount of their daily catch; those are paid after the season or sometimes after a few days when the trader sells the abalone. The price then is generally higher than the cash price, unless the trader makes a loss in selling the product, in which case they will be paid less according to the cash price of each day during the season. For example, in 2003 the price was O.R. 60/kg of fresh flesh by register, while the cash price was O.R. 55/kg. During the buying and selling process, some of the divers' catch may be rejected from the weighing scale, because of being deeply sliced and injured.

Some divers might ask the traders to give them a loan or buy them a four wheel-drive vehicle, in consideration of what they will gain from the season, and in this way they become obliged to dive and sell their catch to that trader without getting any cash money. Recently, some divers have begun to co-operate and collect their catch as one group; and at the end of the season, one or two of them travel to Hong Kong to sell their harvest. By doing this, they can gain a better price for their products.

According to Johnson *et al.*, (1992), during the 1981-2 fishing season, abalone was sold by the piece, and the price was O.R. 1 for four pieces (US$ 2.59), irrespective of size. The price increased to O.R. 2 for three pieces in 1986-7, then to O.R. 1 per piece in 1988-9. In 1988, the traders changed to payment by weight, and the price was O.R. 21/kg of fresh meat, (about US$ 54/kg). Thereafter, the price continued to rise to reach O.R. 50/kg for fresh flesh in 1992 then fluctuated at around O.R. 45/kg. The price peaked at about O.R. 68/kg for fresh flesh (US$ 177/kg) in 1997. In 2003, divers were paid O.R. 55/kg of fresh meat (Figure 2.5).

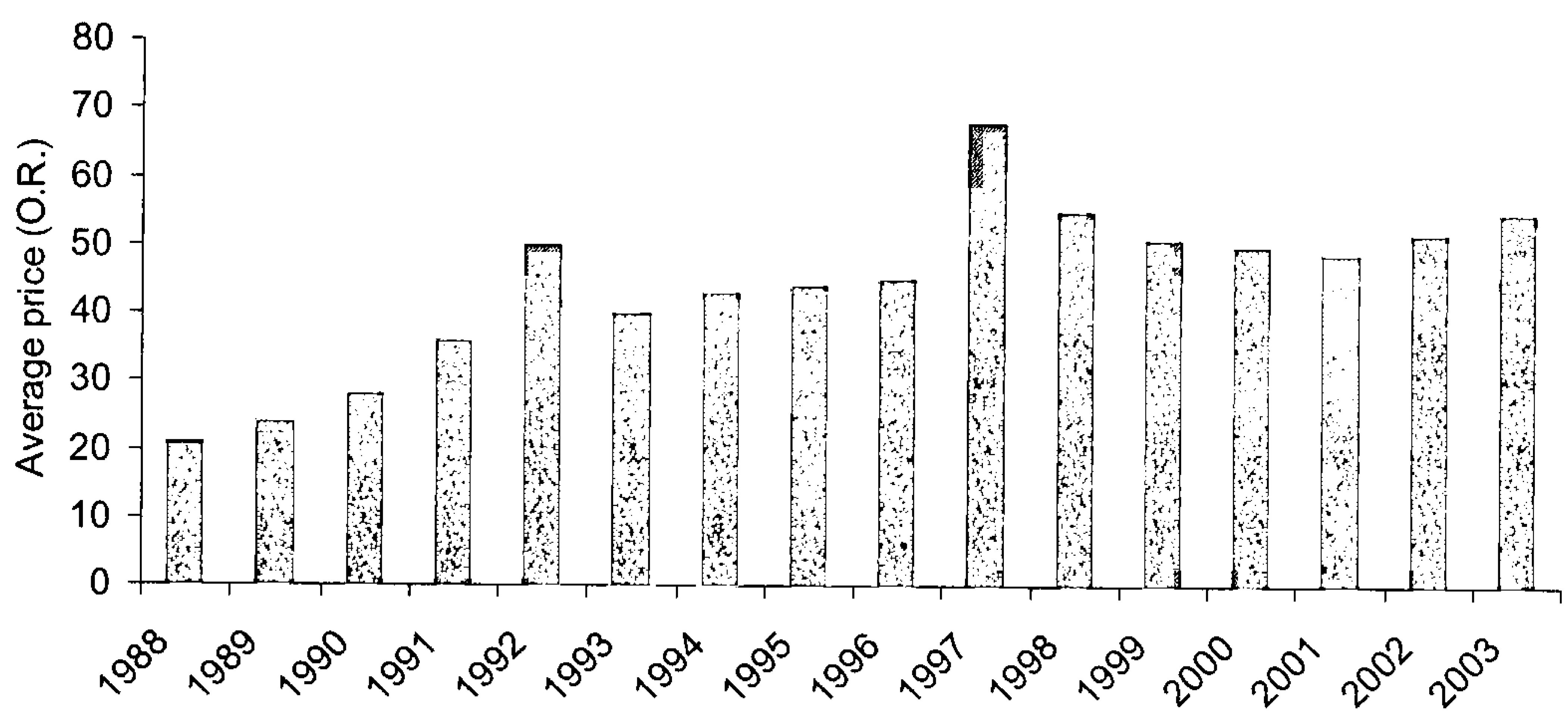


Figure 2.5 Average abalone price (O.R./kg) during 1988-2003

Due to the high price in the international market, most of the abalone production is to be exported, and the local market is only supplied in small quantities, usually of small sized individuals that have been rejected by traders. This is an infrequent supply, from illegal catches, which are marketed by some women in the traditional local market. The lack of steady supply is reflected in the high price. The local market price is O.R. 1 (US$ 2.5) for one piece of abalone, the size of a thumbnail.

Weight for weight, the price for dried abalone is about three times the price for fresh abalone. It is between O.R. 135-200/kg (US$ 350-519), as one kilogram of dried abalone is produced by and equal to three kilograms wet weight. This high price is due to the high demand from the international market, and it reflects the importance of the resource to the divers, as well as for the country.

Until the early 1990s, the abalone shells were discarded on the shore or accumulated near the collecting camps where the divers usually processed their harvest; they had no value. In recent years, however, most have been exported to South Asia and Egypt for use in various handicraft industries. The present price is between O.R. 3-6 for a sack of shells.

The total divers' revenue for the diving season during 1988 (six month season), was 4359 Omani Rials (US$ 11322) with the highest revenue in November O.R. 967 (US$ 2514) for 20 fishing days and lowest in January O.R. 462 (US$ 1200) for the same number of fishing days (see Table 2.1 in previous section). This dropped to O.R. 1997 in 1998, associated with a fall in catch to 31 t valued at 1.7 million (US$ 4.4 million). This was estimated on the basis of local price of O.R. 55/kg of fresh meat, since the export prices are unknown and kept secret between the abalone traders. Although the price increased from 21 Omani Rials for a kilogram of fresh flesh (US$ 54.5) in 1988 to O.R. 68 (US$ 177) in 1997, the revenue for the divers decreased from O.R. 4359 (US$ 11322) in 1988 to O. R. 2979 (US$ 7738) in 1997. This was because of the decrease in landing due to increase in the number of divers from 244 divers in 1988 to 848 in 1997, besides the decline in the stock density (Table 2.2).

Table 2.2: Grand total of abalone catch (kg), value (×1000 O.R.), abalone average price O.R./kg, effort (number of divers, total number of fishing days), catch/day/diver, and diver's revenue, between 1988 - 2003 in Oman

Year	Catch (kg)	Value (X 1000 O.R.)	Average Price (O.R.)	Number of Divers	Total N.F.days	Catch/day (kg)	Diver's Revenue(OR)
1988	50565	1062	21	244	25113	2.11	4359
1989	41864	963	24	281	25261	1.6	3460
1990	44233	1201	28	277	24591	1.6	4034
1991	43054	1550	36	840	22554	1.9	1852
1992	41644	2082	50	846	24688	1.63	2370
1993	34054	1362	40	725	16409	1.85	1709
1994	36138	1500	43	860	17190	2	1694
1995	42505	1870	44	989	24434	1.6	1745
1996	42679	1921	45	791	24305	1.95	2248
1997	39739	2702	68	848	22661	1.69	2979
1998	31695	1704	55	729	22655	1.25	1997
1999	28682	1434	51	508	13814	1.77	2115
2000	44480	2249	50	1169	20502	3.02	1835
2001	50853	2478	49	772	21691	1.82	2035
2002	49504	2597	52	1024	25632	2.01	1819
2003	56379	3077	55	951	21528	2.04	2437

2.8 Aquaculture and Prospects for Stock Enhancement

There is increasing interest and investment in abalone aquaculture throughout the world. Aquaculture production for China and Taiwan together in 2002 was of the order of 7500 t. This production is high considering that world production from wild abalone fisheries was approximately 22677 t in 2002 (Gordon & Cook 2004).

In Oman, there is no history of aquaculture. Because of the dramatic decline in commercially-harvested abalone in the last few years, the Ministry of Agriculture and Fisheries has requested technical cooperation from Japan, which has highly developed technology for seed production and culture of abalone, and produces seed for stocking. This ranching in Japan is claimed to make a significant contribution to their fishery management and commercial catches (Uki, 1989).

The Oman request was to investigate the possibility of producing abalone seed for *Haliotis mariae* to identify the possibility of culturing the Omani abalone to a commercial size, and to improve and maintain the over-exploited stock through providing seed stock that can be released to supplement natural recruitment and maintain the degraded fishing grounds.

A research programme was conducted in 1993 and from 1995 to 1997. This programme was coordinated and partly funded by Japan International Cooperation Agency (JICA). The project demonstrated the possibility of abalone seed production and culture in Oman, and has produced some promising results (Iwao, 2000). Procedures for producing, seedling and culturing Omani abalone (*Haliotis mariae)* were developed during these activities. The project continues, and is providing impetus for encouraging Omani investors, although to date there is no commercial abalone aquaculture farming. However, in 2005 some licences to culture abalone were issued, and there are some applications for licences to culture abalone before the Inter Departmental Committee for Aquaculture.

2.9 Socio-economic Considerations

Fishery resource assessment and management requires an understanding of the behaviour and attitudes of fishers, because desires for food and income always drive the fishing behaviour. In addition, social and religious aspects can have marked effects, and so, it is important to understand the cultural aspects driving fishery communities, including gender issues, as women also practise diving.

In Oman, most of the small towns along the southern coastline between Mirbat and Sharbithat in the Dhofar region are economically dependent on fisheries. Abalone fisheries were for many years a valuable and important resource providing an economic base for societies in these areas. Furthermore, while the catch of this fishery might be relatively small, the wealth created through the high price of this product can be considerable. The landed value of abalone fisheries was 3.08 million Omani Rial (US$ 8.4 million) in 2003, representing about 4.9% of the total value of all fisheries production in Oman (Table 2.3) (Dept. of Statistics, 2003).

Table 2.3 Grand total catch and value of whole fisheries sector, abalone catch and value, percentage of contribution during the period 1988-2003

Year	Grand Total of Fisheries sector		Abalone Catch and Value and Percentage			
	Catch (t)	Value (x 1000 O.R.)	Catch (t)	Catch %	Value (x 1000 O.R.)	Value %
1988	166079	33950	51	0.03	1062	3.1
1989	117537	33430	42	0.04	963	2.9
1990	118641	34620	44	0.04	1201	3.5
1991	117765	28347	43	0.04	1550	5.5
1992	112313	32626	42	0.04	2082	6.4
1993	116469	34300	34	0.03	1362	4
1994	118572	38370	36	0.03	1500	3.9
1995	139861	60872	43	0.03	1870	3.1
1996	121615	53819	43	0.04	1921	3.6
1997	118994	59410	40	0.03	2702	4.6
1998	106165	54418	32	0.03	1704	3.1
1999	108809	55516	29	0.03	1434	2.6
2000	120421	52766	45	0.04	2249	4.3
2001	129904	54064	51	0.04	2477	4.6
2002	142668	61151	50	0.04	2597	4.2
2003	138485	62855	56	0.04	3076	4.9

The Ministry of Agriculture and Fisheries seek to protect this small fishery, but the local fishermen catch small immature abalone below the legal size, collect abalone out of season, and destroy the habitat by turning over the boulders. This is because many poor people consider the sea the only potential source of food and income and the fisheries are viewed as common property, an open access resource. As such, there is little to be gained by one fisher trying to conserve the resource because the abalone will simply be taken by someone else in the absence of law enforcement. The race to collect abalone has been particularly dramatic in the remote areas where management systems have failed to control the fishing process. This arises because divers consider it better to catch the abalone today even it is small, rather to leave it to grow, when it might be collected by another diver.

Women also practise diving in this region, and as the number of divers entering the fisheries has increased rapidly, so they are faced with declining catches, lacking any alternative source of income.

Diving is a dangerous job and coastal communities live with the omnipresent risk of losing loved ones at sea. In the case of any fatal accident, whatever and wherever it is, as all the fishing communities share the same religion, this affects their fishing behaviour, and most divers stop working during that day and perhaps for a few more days. On Friday, it is the tradition that many divers do not dive because this is a holy day and they might have it for rest. Diving days are also, sometimes, affected by some social activities such as weddings, and national festivals, in which many divers like to participate. Fishing pressure might, however, be increased during the following days.

CHAPTER 3

BIOLOGICAL ASPECTS OF THE OMANI ABALONE (*Haliotis mariae*)

3.1 Introduction

This chapter reports the investigation on the biological aspects of *Haliotis mariae* at the southern region of Oman. It identifies the stock status and provides information on factors that influence the fishery sustainability.

General topography of the Dhofar Province and study area

Barratt *et al.* (1984) and Savidge *et al.* (1986) described the general topography of the coastline in this region. It is irregular and characterised by a chain of high mountains (Jebal Al'Qmar, Jebal Al'Qara, Jabel Samhan) interspersed by long sandy beaches, the longest of which extends from Raysut to Mirbat, a distance of some 85 kms, broken by some rocky outcrops at Taqah. The Jabel Samhan, east of Salalah has the highest elevation, with a recorded highest spot of 2100 metres. On most sections of the coast the mountains reach unbroken to the sea. Beyond Salalah to the east, the mountains are pushed further inland and separated from the coast by an extensive plain, primarily composed of gravel and sand. The intertidal region here is dominated by long, fine sandy beaches with patchy mangrove stands.

The rocky shores west of Salalah are essentially composed of compacted fossiliferous limestones, and are extensions of the Jebal Al'Qamar (Raysut and Al'Mughsail); the immediate foreshore is backed by cliffs, which, because of the nature of the rock, are heavily eroded by the oceanic swell. These cliffs are severely undercut at their bases, and have scattered boulders, both of which give rise to specific types of flora and fauna. The main intertidal zone is again composed of compacted limestone, but forms a plateau, some 50-70 metres wide, which shelves gradually to the sub-littoral. These soft sedimentary rocks give rise to rock pools, depressions and gullies, ideal habitat for burrowing fauna.

A contrast to the general pattern can be found on the rocky shores of the eastern region, from Mirbat to Sadah, where the soft, sedimentary limestone rocks have been eroded away to reveal an underlying stratum of much harder rocks, metamorphic in character. These granite substrates fall into two categories. Around the Mirbat area, and extending as far as Ras Gingiri, the sedimentary rocks of Jabal Samhan lead onto an extensive sand and gravel plain, and it is only in the immediate coastal zone that underlying metamorphic rocks are revealed; thus, the shoreline in this area is composed of a mixture of sandy beaches and low lying metamorphic rocks. By contrast, from Ras Gingiri past Sadah and on towards Hasik, the elevation of the immediate foreshore is raised much higher than in the Mirbat region, with the consequence that the shore in many places is virtually inaccessible, due to a virtually impenetrable chain of coastal mountains. This area is again composed of metamorphic rocks which have been exposed by erosion of the softer, overlying limestone sediments. It is the most extensive area of metamorphic rock in the Dhofar region and may well have some bearing on the localised intensity of the upwelling in this area. These harder rock types produce many cracks and crevices in the rock surface, and give rise to a flora and fauna more readily adapted to this kind of habitat.

Towards the eastern end of the Dhofar coastline is situated Ash'Shuwaymiyah followed by Sharbathat, the last town of Dhofar province. The coastline between these two regions comprises long sandy shores intersected by a zone of low limestone cliffs to the east at Mangi. The coast beyond Sharbithat and towards Soqarah is similar to that between Ras Gingri and Sadah, and is virtually inaccessible due to a virtually impenetrable chain of coastal mountains (Figure 3.1).

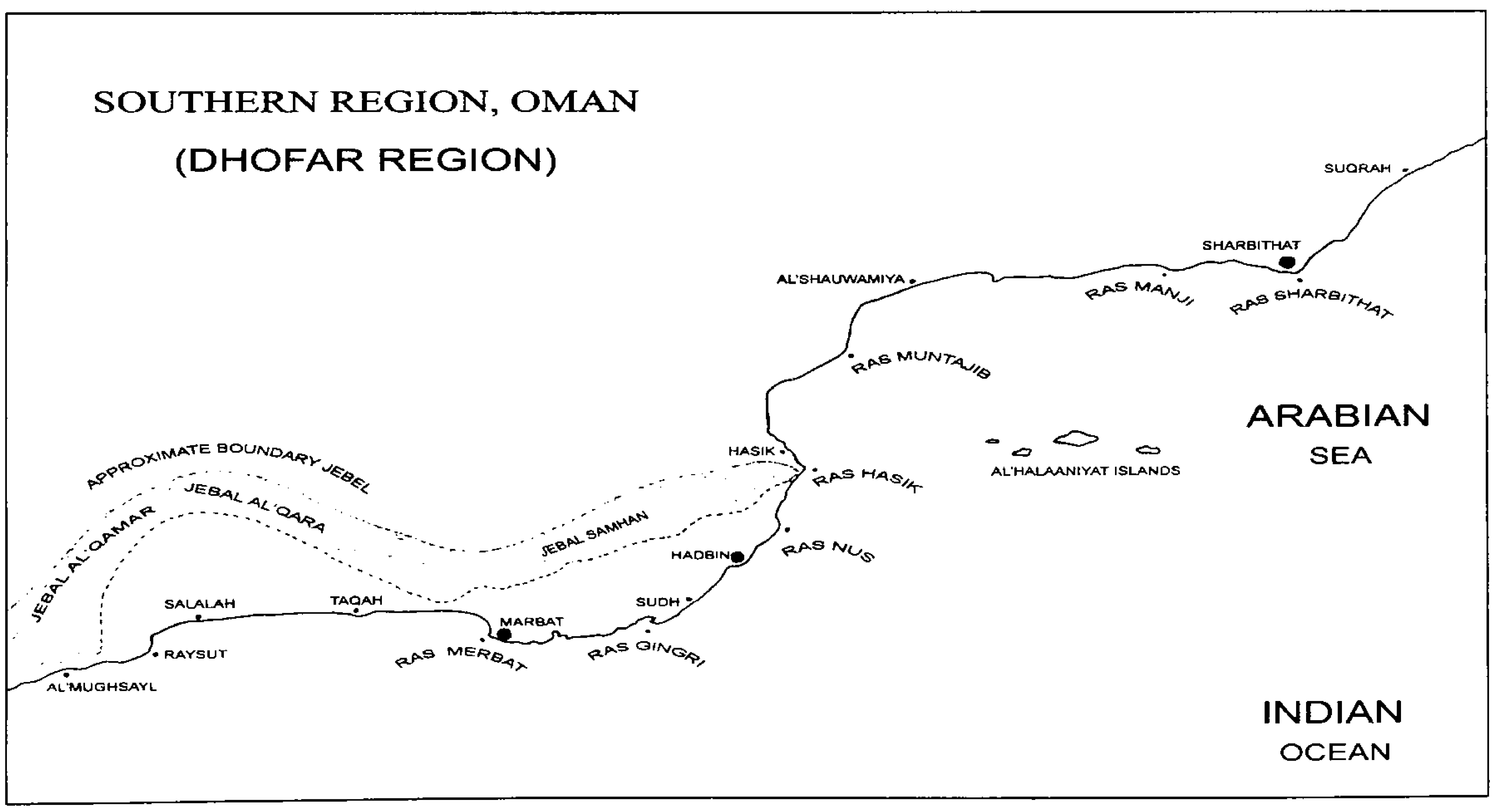


Figure 3.1 Illustration of the southern coastline of Oman and the study sites (Mirbat, Hadbin and Sharbithat).

The sublittoral topography differs significantly between the eastern and western coast in the extent of the continental shelf and the steepness of the drop-off into deeper water (500 fathoms +) (Barratt *et al.* 1984). Thus, in the immediate Salalah region the continental shelf extends some 50 kilometres offshore, and subsequently shelves quickly to a depth of 500 metres at approximately 70 kilometres offshore. In contrast, in the coast beyond Ras Mirbat to the east, the edge of the shelf is only some 10 kilometres from the coastline, and the corresponding 500 metres depth lies only another 10 kilometres further on. The seaward sides of Al'Halaneyat Islands follow the same pattern and are reported to be the centre of the upwelling. The net effect of these features will be to enhance the strength and intensity of the upwelling in the eastern region compared with the less effect in the western coast (Barratt *et al.*, 1984)

The surface water moved off by the monsoon wind, is replaced by water from much deeper in the ocean in the eastern coast than in the western one, owing to the much steeper sublittoral topography. This water will characteristically be colder and bear a higher supply of nutrients, and these factors are involved in the selective distribution of kelp forests (main food source for abalone) along the eastern coast, mainly around the Sudah region, and subsequently the restricted distribution of the abalone *Haliotis mariae* to this area (Barratt *et al.*, 1984).

3.2 Materials and Methods

3.2.1 Study sites and sampling procedure

This study was carried out along the eastern coast of Dhofar province between Ras Mirbat 16° 57' N, 54° 42' E and Sharbithat 17° 58' N, 56° 23' E at three selected stations: Mirbat 16° 58' N, 54° 41' E, Hadbin 17° 08' N, 55° 11' E and Sharbithat 17° 55' N, 56° 21' E. (Figure 3.1). The stations were selected on the basis of abalone distribution range and the commercial importance of these sites as a main fishing ground. In these areas, *Haliotis mariae* are found attached to the lower surfaces of overhanging rocks and crevices in the intertidal zone. Specimens were therefore collected by diving with the aid of self-contained underwater breathing apparatus (SCUBA). 50 individuals of *H. mariae* were sampled from each of the three sites on a monthly basis for a period of 24 months between April 2003 and March 2005. However, at Sharbithat station sampling was stopped during the monsoon season

(June, July and August) because of the rough sea in this area, which made it impossible to reach the sampling ground. In addition the monthly 50 samples were not completed at Mirbat station during some months due to scarcity of abalone or low visibility. A total of 3231 wild abalone were examined during the period of this study: 1171 individuals from Mirbat, 1200 from Hadbin and 842 from Sharbithat. The samples were brought live to the laboratory at Mirbat Abalone Seed Production Station, where the whole work of this project was undertaken. The samples were cleaned and examined for different studies. The environmental parameters in the study sites were recorded during the sampling period. The divers' landings during the 2003 fishing season at main landing sites Mirbat, Hadbin and Sharbithat, were sampled and examined. In addition, a mark and recapture experiment was conducted for one year during the project period. Also, another experiment on abalone drying and weight losses during the preservation process was undertaken during this study. This study aims to provide information on the annual changes in the fishery and its important related aspects.

3.2.2 Environmental conditions

Salinity, dissolved oxygen, pH, and temperature reading were recorded using a Hydrolab device at the three study stations on a monthly basis for a period of 24 months. The monthly parameter readings were graphically plotted.

3.2.3 Samples during the fishing season (Divers' landings samples)

In this study, 6000 freshly dislodged shells were randomly sampled from commercial divers' landings: 2000 shells at each of the three main landing sites Mirbat, Hadbin and Sharbithat, during the 2003 fishing season. The divers usually landed their harvest whole, then removed the muscle from the shell on the shore, to sell the flesh to the abalone traders, while the shells accumulated around the trader camps. Shell length (SL) was measured and recorded for each sample to the nearest 0.1 mm by using Vernier calipers, and sex was determined by visual inspection of the gonad. The samples were representative of different zones as they were obtained from both shallow and deep water. This was to determine the length frequencies and estimate the illegal catch within the landings.

3.2.4 Morphometry

Understanding the relationship between shell dimensions and body weight of abalone is useful in fisheries studies; it helps to establish the various yield parameters and to convert one variable into the other (King, 1995).

The length and width of each shell of the 50 monthly samples from the three stations, was measured to the nearest 0.1 millimetre with Vernier callipers. Total weight was recorded to the nearest 0.1 gram after removal of epizoic matter. The soft body was dissected from the shell and weighed, the flesh (foot muscle) was dissection from the viscera and weighed, and the shell weight was calculated.

The following morphological data were recorded for each abalone sample:

- Shell length (mm)
- Shell width (mm)
- Total weight (g)
- Soft body weight (foot muscle + viscera) (g)
- Flesh weight (foot muscle) (g)
- Shell weight (g)

Relationships of total weight, foot weight and shell weight, with shell length were examined for *Haliotis mariae* from the three stations: 1171 individuals from Mirbat, 1200 from Hadbin and 842 from Sharbithat.

The relationship between length, L and weight, W was derived by the equation:

$$W = a\,L^{b}$$

where a and b are parameters of the power relationship; a is a constant and b the exponent. On linear transformation, this equation becomes:

$$\log W = \log a + b\,(\log L)$$

where b represents the slope of the line and it is an estimate of the rate of increase in weight, and log a is the origin of the fitted lines.

3.2.5 Size composition of samples (Length frequency)

Shell lengths of the 50 monthly samples were used to examine the changes in shell size distribution throughout the year. The shell length groups for each month were graphically plotted against their frequency. The total number of samples examined during the two years was Mirbat 1171 individuals, Hadbin 1200 and Sharbithat 842.

3.2.6 Sex ratio

The 50 individuals sampled at each site each month were used, and sexes of *Haliotis mariae* were determined by visual inspection of the gonad colour. Mature male gonads appear creamy white whereas the mature female gonads are dark green, and those of sexually immature specimens are grey. Similar colour differences occur in most other species of *Haliotis* (Boolootain *et al.*, 1962; Newman 1967). The sex was confirmed later through gonad cross section study (Gonad index, GI). The monthly distribution of male and females within the samples was examined throughout the two years and the sex ratio was calculated. The total number of samples examined during the two years was Mirbat 1171 individuals, Hadbin 1200 and Sharbithat 842.

3.2.7 Gonad Index and spawning season

Gonad index (GI) is a good method for determining the spawning season by observing the seasonal changes in gonad development. This method has been widely used in several abalone species (Ino & Harada, 1961; Boolootain *et al.*, 1962; Newman, 1967; Shepherd & Laws, 1974; Bussaawit *et al.*, 1990).

For the 50 monthly samples collected during the two years (Mirbat 1171 individuals, Hadbin 1200 and Sharbithat 842), the conical appendage, which contains the gonad and hepatic tissue, was separated from the rest of the animal and kept in the freezer at -25 °C for 12 hours. Cross-sections (2 mm thick layer) were then taken at the base of the conical appendage. The cross-sections were photographed by digital camera, and printed on a standard 180g glossy paper. By tracing the perimeters of the specific cross-sections of the gonad and the hepatic tissues, the photographed areas for both gonad and hepatic gland were separately cut from the sheet and weighed. The area was used as an index of gonad volume because measuring gonad volume directly is very time-consuming. The validity of this approach has been established by Nash *et al.*, (1994) who demonstrated that gonad area is closely and linearly related to gonad volume in blacklip abalone.

The gonad index (GI) was calculated as a proportion of the gonad area weight of the total area weight by the weight of the photographed area for both the gonad area and digestive gland area of the cross section and using:

$$GI = (GW/ DW+GW) \times 100$$

where:

GI is the Gonad index.

GW is the Gonad area weight.

DW is the digestive gland area weight (hepatic gland)

3.2.8 Maturity stages

The maturation stages of the monthly 50 *Haliotis mariae* individuals sampled from each of the three stations were investigated (total number of samples: Mirbat 1171, Hadbin 1200, and Sharbithat 842). For each abalone, sex and maturity stage were determined by visual inspection of the gonad colour and gonad bulk. The gonad maturity was determined on a scale of 0-3. Zero represents no development at all (sex cannot be determined); stage 1 is when the sexes can be distinguished and the gonad starts to develop below the shell periphery; stage 2 is when the gonad is slightly developed to reach the level of the shell periphery; and stage 3 is when the gonad is well developed, expanding beyond the shell periphery. The annual reproductive cycle of *H. mariae* was confirmed through percentage frequencies of different gonad maturity stages.

3.2.9 Size at first maturity

Knowledge of the size at which the abalone *Haliotis mariae* reaches maturity is of value and critically important in management strategies such as the introduction of minimum legal sizes, which depend on reproduction occurring prior to the onset of fishing (Shepherd & Johnson, 1991). This is to protect enough individuals and to ensure that small abalones which have not spawned even once may have an opportunity to reproduce before being harvested and collected by the divers. For this purpose the 50 monthly samples of *Haliotis mariae* from each of three stations were measured and examined for their maturity stages throughout two years. The data were analysed in relation to maturity stages at each site, and the accumulated percentage occurrence of individuals in advanced maturity stages is graphically plotted against length groups. The size at which 50 per cent of all individuals are sexually mature at advanced stage of development is taken to be the size at first maturity (King, 1995). The total number of samples used in this study was 1171 individuals from Mirbat, 1200 from Hadbin, and 842 from Sharbithat.

3.2.10 Growth

The abalone is known to have seasonal growth cycles, but the growth rate is not consistent. Marking of individual animals, releasing and recapturing them a year later (or multiples of a year), is considered a reliable and good method to determine the annual growth rates. Shepherd & Johnson (1991) and Day & Fleming (1992) reported, that as growth of abalone often varies seasonally, the periods between tagging and recapture of the samples should not be less than a year.

In the present study, marking and recapture of samples after a period of one year was used to estimate the growth rate for *Haliotis mariae*. The experiment was carried out near Mirbat (16°, 57.923 N, 054°, 42.383 E) in the Southern region of Oman, between April 2004 and April 2005. A total number of 197 abalone of small size specimens ranging in size between 39.3 mm and 78.1 mm SL, with mean shell length 59 mm, and weight between 6.2 g and 64.7 g with an average of 26.4 g were collected from the wild. The samples were tagged with labels using marine epoxy glue following the procedure described by McShane (1988), and allowed to recover from the tagging stress in aquaculture tanks at Mirbat Abalone Seed Production Station, and monitored for 10 days before being returned to the seabed. The shell length, animal weight, sex, and maturation stage data for each specimen were recorded. A well-defined sheltered site of natural abalone habitat at depth of 4-9 m was selected to improve the chances of recapture. The samples were returned to their selected nature environment site and placed attached to the under rocks and in crevices; the samples were adapted to the water temperature prior to the sea bottom return.

One of the main reasons for determining the growth rate for *Haliotis mariae* in this experiment is because many divers of this species have alleged that they used to hide small juvenile abalone in open crevices which they blocked with rocks and boulders, and within just a few months they harvested them at large sizes.

The abalone divers were notified that *Haliotis mariae* had been tagged and returned to the sea, without being notified of the release site. Divers were requested not to collect or disturb the tagged abalone, if found, until a year after released. Effort could then be made to recover the tagged abalone, with a later notice requesting the divers to inform Raysut Fisheries Research Laboratory about any tagged abalone found within their harvest during the fishing season. Another 37 wild samples ranging in size between 40.3 mm and 74.8 mm SL with an average shell length of 62 mm, and ranging in weight between 9 g and 56.1 g with an average weight of 30.7 g, were treated using the same procedures and kept in water tanks at Mirbat Abalone Seed Productions Station for a period of one year with daily natural *Ulva* sp. and artificial feeding. An intensive survey was conducted one year later to recover the tagged abalone. Searching for the tagged samples continued for three days until recovery rates approached zero. The area searched extended up to 100 metres either side of the release site.

All the previous measurements for each recovered sample were recorded to calculate the growth in length and weight over a period of one year; also the sex and changes in maturation stages were observed. The same measurements were taken for the tagged samples in the aquaculture tanks.

3.2.11 Proximate biochemical composition

In the absence of previous study on changes in biochemical composition for *Haliotis mariae*, the biochemical composition profile of foot muscles for wild-caught abalone was examined. The aim was to determine the seasonal changes in the biochemical composition for both sexes in relation to the seasonal variation in availability of macroalgae and in relation to the reproductive season, to assess variation in nutritive values and determine the best time for harvesting, taking into account the spawning season. Changes in biochemical composition may be used as an indicator of seasonal changes in growth rates, and the quality of foot tissue. This information will contribute to the knowledge on *Haliotis mariae* biology and on the quality of the flesh product.

For this study, foot muscles of adult male and female wild abalone *Haliotis mariae* were collected monthly from the three study stations during the two years were used. The foot muscles of samples were maintained frozen at -30 °C until sent for laboratory analysis carried out by the Quality Control Centre Laboratory, Ministry of Agriculture and Fisheries, Muscat, Oman.

The analyses were performed on two monthly selected samples of male and female abalone from each station and were done in duplicate (average percentages from two trials). Proximate biochemical composition analysis to determine moisture, protein, lipid, ash and carbohydrate levels in abalone foot muscles was conducted using standard methods (AOAC, 1990). Moisture was calculated following drying 12-15g of sample at 100 C° for 40 minutes using an Infrared Moisture Determination Balance. Protein content was determined according to the Kjedahl method (through the estimation of kjeldahl nitrogen using an automated Kjeltech 1030, Tecator, Sweden). Total lipid was determined after chloroform: methanol extraction, according to Folch *et al.*, (1957) by using the Soxhlet method. Ash was determined following the dry ashing method by burning 2.5g of sample for 12 hours in a muffle furnace at 550 °C. Carbohydrate percentage was calculated as the remaining percentage of 100 minus the sum of the percentages of moisture, protein, fat, and ash (QCC, Laboratory Notes).

Measurement of biochemical composition

Moisture: Moisture content is a measure of the amount of water contained in a sample. Water can be bound to the chemical components in the seafood either loosely (free) or tightly. Loosely bound water is driven off first when the sample is placed into an oven. Moisture was determined by drying 12-15g of sample at 100 C° for 40 minutes by using an Infrared Moisture Determination Balance. Samples were spread evenly on an empty aluminum and placed on the measuring plate. The moisture meter measures the moisture content automatically and gives percentage values (QCC, Lab. Notes).

Protein: Protein content was determined according to the Kjeldahl method (through the estimation of kjeldahl nitrogen using an automated Kjeltech 1030, Tecator, Sweden). It is the most frequently used procedure for the measurement of protein for almost every type of commodity. The procedure utilizes sulphuric acid, which hydrolyses and converts all the protein nitrogen to the stable compound ammonium sulphate. Under alkaline conditions ammonia gas is liberated from the ammonium sulphate and trapped in boric acid, which becomes neutralized. The degree of neutralization of the boric acid can be determined by titration with acid and depends on the amount of nitrogen in the original samples. Nitrogen represents 16% of the total weight of the average protein and 6.25 is used as the conversion factor. Values of % protein are presented in display which when divided by sample weight gives actual % protein (QCC, Lab. Notes).

% Protein = % Nitrogen / Weight of sample

Fat: The Soxhlet method for fat determination is based on the solubility of the free lipid content, which consists essentially of neutral fats (triglycerides) and free fatty acids in less polar solvents such as petroleum ether and ethyl ether. After extraction, the solvent is evaporated and the residue weighed.

The extraction of lipid using the Soxhlet method is widely used for grains, flours and other non-animal products, where the majority of the lipids are of a neutral type. However, the use of chloroform/ methanol allows the procedure to extract both membrane and neutral lipid and hence works well for the extraction of lipid from seafood (QCC, Lab. Notes).

$$\%\ \text{of Lipid (dry basis)} = \frac{(\text{Weight of Beakers} + \text{Fat}) - (\text{Weight of Beakers})\ x100}{\text{Weight of Sample}}$$

$$\%\ \text{of Lipid (wet basis)} = \frac{[100\ x\ \%\ \text{of Fat (dry basis)}] - [\%\ \text{of Fat (dry basis)}\ x\ \%\ \text{of Moisture}]}{100}$$

Ash: Ash is a measure of the total inorganic component of a sample, which is made up substantially of minerals. Two methods of ashing are commonly used: 1) wet ashing in which organic compounds are degraded by digesting samples in an oxidizing acid such as nitric or percholoric acid, or 2) dry ashing, which takes place in a furnace at temperatures ranging between 400°C and 700°C. Dry ashing is the most common methods used to determine the total mineral content of seafood. The residue must be free of carbon. This means that the ash must appear white with no black regions. If carbon remains the residue can be treated with a few drops of hydrogen peroxide and then re-ashed (QCC, Lab. Notes).

Carbohydrate: Carbohydrate was estimated as follows;

% Carbohydrate =100 - % (Moisture + Protein + Fat + Ash)

(QCC, Lab. Notes).

3.2.12 Abalone preservation (Drying process and weight losses)

Processing of dried abalone is one of the most important activities of the abalone traders. This traditional preservation method usually takes place in the traders' collecting camps during the fishing season. After the meat has been separated from the shell by the divers and sold to the abalone traders, it is collected in a large plastic or metal pail. When there is enough to fill the cooking vessel, it is transported to the back area of the camps where it is spin washed many times and then cooked on a wood fire (charcoal) in a very simple way; by boiling the abalone foot muscles in sea water diluted with fresh water in a ratio of 2:1 respectively, for 80 minutes. The cooked abalone are then spread out on wooden meshed stands and sun dried for about two weeks, and turned periodically, until they are dried and have turned golden in colour.

The abalone are then graded into different sizes and packaged for export to South East Asian markets. This dried abalone can be preserved for over a year and has always been regarded as a delicacy by the Chinese. Even though dry abalone can fetch high prices, about 3 kg of raw abalone muscles is required to form 1kg of dried abalone.

In order to find out the weight of the final product and the percentage of losses in weight during the drying process, and the optimum time required for the best drying and less loss among different size groups (illegal and legal sizes), an attempt was made to determine the ratio between the wet weight and dry weight of these two groups to find out a standard ratio for economic and conservation purposes.

The experiment was performed at the traders' camps during the fishing season, under the same drying conditions, and following the same traditional method used by them. The wet weight of the flesh (foot muscle) for 47 abalone samples of different size groups (<90mm & >90mm) was recorded and the samples were marked and treated according to the traders' preservation method. The samples were sun dried for 18 days and the weight of each sample was recorded on several days during the drying period. The weight loss was calculated during the drying days, and the weight and percentage of the final product as well as the optimum drying time were obtained.

3.3 Results

3.3.1 Environmental conditions

Water temperature showed a distinct seasonal cycle that was common at all sites (Figure 3.2). Temperature was relatively stable at around 25 °C between November and May but falloff between June and August. This decline was associated with the upwelling period. Salinity and pH in all the stations showed no significant changes year around (Figures 3.3 & 3.4). Dissolved oxygen fluctuated within months, but with no obvious trends (Figure 3.5).

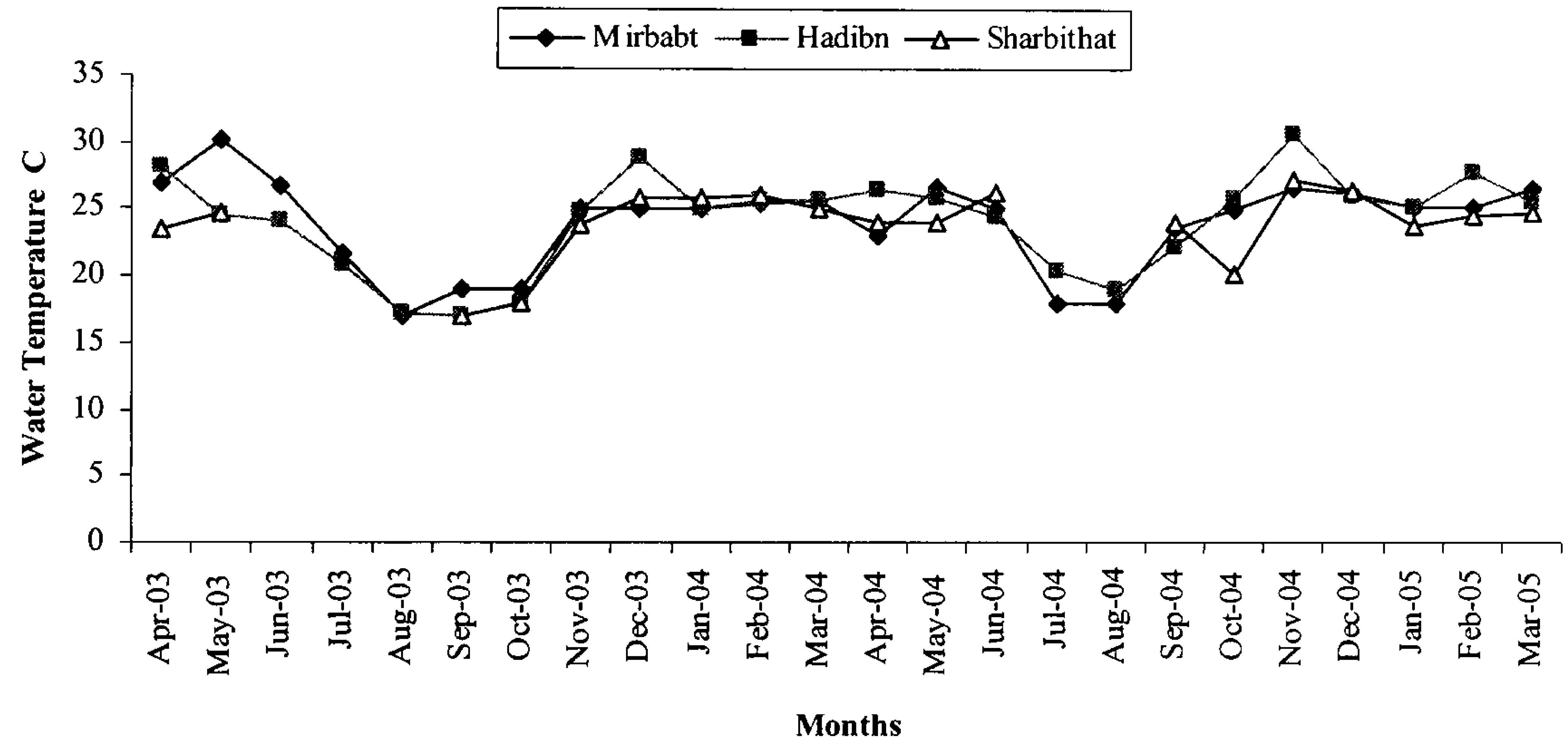


Figure 3.2 Seasonal changes in sea temperature recorded between April 2003 and March 2005 at three shore stations (Mirbat, Hadbin and Sharbithat).

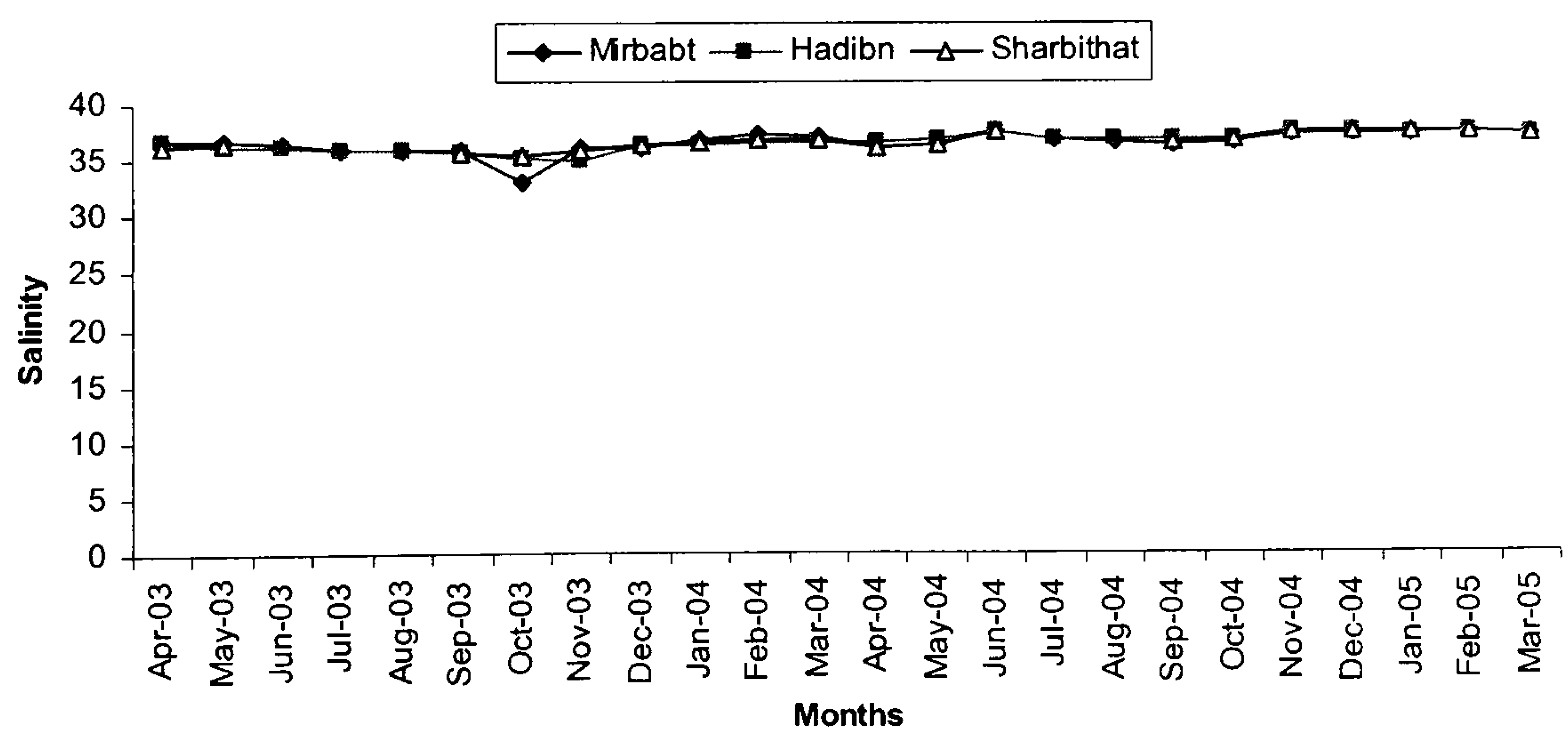


Figure 3.3 Seasonal changes in sea water salinity recorded between April 2003 and March 2005 at three shore stations (Mirbat, Hadbin and Sharbithat).

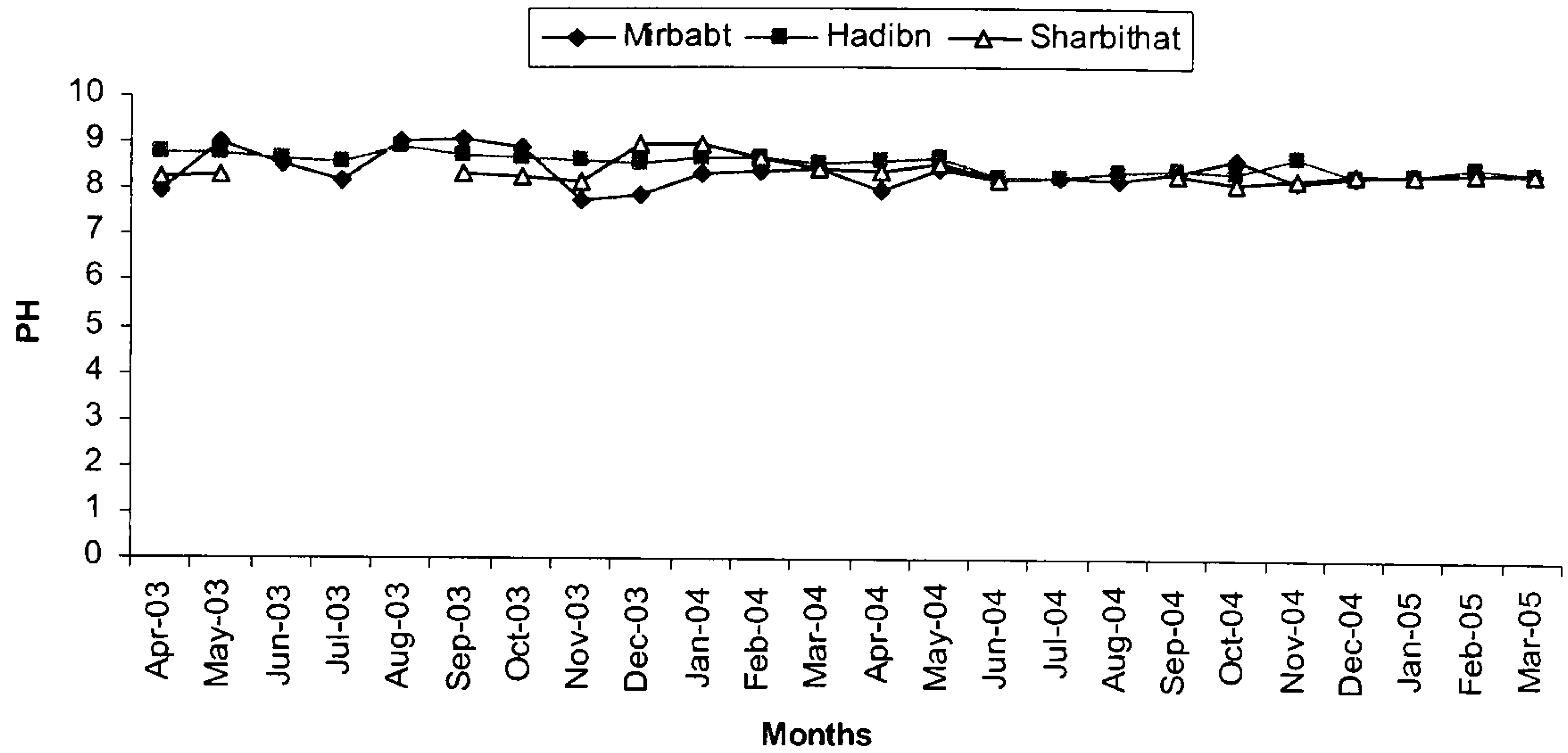


Figure 3.4 Seasonal changes in pH recorded between April 2003 and March 2005 at three shore stations (Mirbat, Hadbin and Sharbithat).

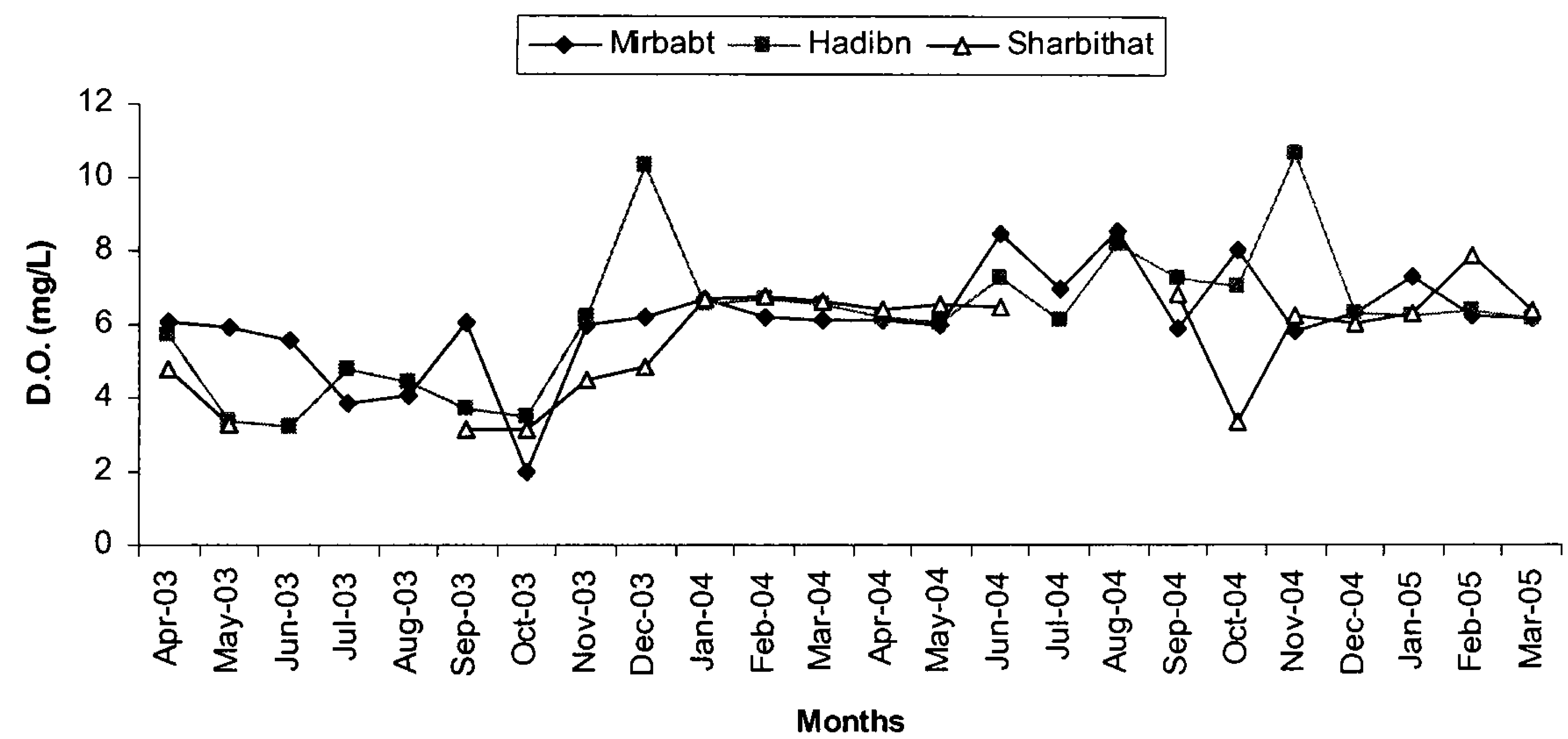


Figure 3.5 Seasonal changes in dissolved oxygen recorded between April 2003 and March 2005 at three shore stations (Mirbat, Hadbin and Sharbithat).

3.3.2 Samples during the fishing season (Divers' landing samples)

Significant numbers of small illegal sizes were found in the landings during the fishing season. Variation in the contribution of small sizes was observed among the three site landings, particularly at Mirbat and Hadbin where the divers' landing consists mostly of small sizes compared with Sharbithat (Table 3.1).

The size composition of the commercial dive landings of *Haliotis mariae* at the three sites varied. The highest landing of illegal sizes was in Mirbat at (57.7%), followed by Hadbin (50.5%), whereas Sharbithat showed lowest illegal landing (26.3%)

(Table 3.1). The average percentage of illegal sizes landed during the 2003 fishing season at all landing sites was 44.8% of the total divers' landing during that year. The greatest number of sites contributing to illegal landing was 42.9% at Mirbat followed by Hadbin 37.6%, whereas Sharbithat was the lowest, 19.5% (Table 3.1).

Table 3.1 The number and percentage of illegal sizes within a sample of the divers' landings (n = 2000) during the fishing season 2003 at the main landing sites, the percentage of sites contribution in the total illegal landing, and sex distribution in the illegal landing.

Landing site	Sample size	No. of illegal size (< 90mm)	% of illegal size	% of sites contribution in illegal catch	illegal distribution by sex		% of illegal size by sex	
					Male	Female	Male	Female
Mirbat	2000	1154	57.7	42.9	524	630	45.40	54.60
Hadbin	2000	1010	50.5	37.6	513	497	50.80	49.20
Sharbithat	2000	525	26.3	19.5	270	255	51.43	48.57
All Sites	**6000**	**2689**	**44.8**	**100**	**1307**	**1382**	**49.21**	**50.79**

The mean size of abalone landed by divers varied among the three sites (Table 3.2). The lowest average size was recorded in Mirbat at 88.6 mm and 87.8 mm SL for male and female respectively, i.e. below the minimum legal size (MLS) of 90 mm. The average size at Hadbin at 90.2 mm and 90.6 mm for male and female respectively was just above the minimum legal size, whereas the highest average size was at Sharbithat at 98.6 mm 97.4 mm for male and female respectively. The smallest and largest sizes in the divers landings were recorded at Sharbithat (Table 3.2).

Table 3.2 The average size (mm) and size rang for male and female abalone *Haliotis mariae* in a sample (n = 2000) of divers landing during the fishing season 2003 at the three main landing sites.

Landing site	Sample size	Average size (mm)		Male size range (mm)		Female size range (mm)	
		Male	Female	Min.	Max.	Min.	Max.
Mirbat	2000	88.6	87.8	61.1	128.8	58	136.7
Hadbin	2000	90.2	90.6	52.6	130.2	44	131
Sharbithat	2000	98.6	97.4	21.4	144.2	22.9	133.9

The distributions of different size groups of abalone in divers' landings at the three sites suggest that the abalone from the Sharbithat population were larger than those from Mirbat and Hadbin. At Sharbithat the largest size group found was 90-100 mm shell length, whereas in both Mirbat and Hadbin, it was 80-90 mm shell length.

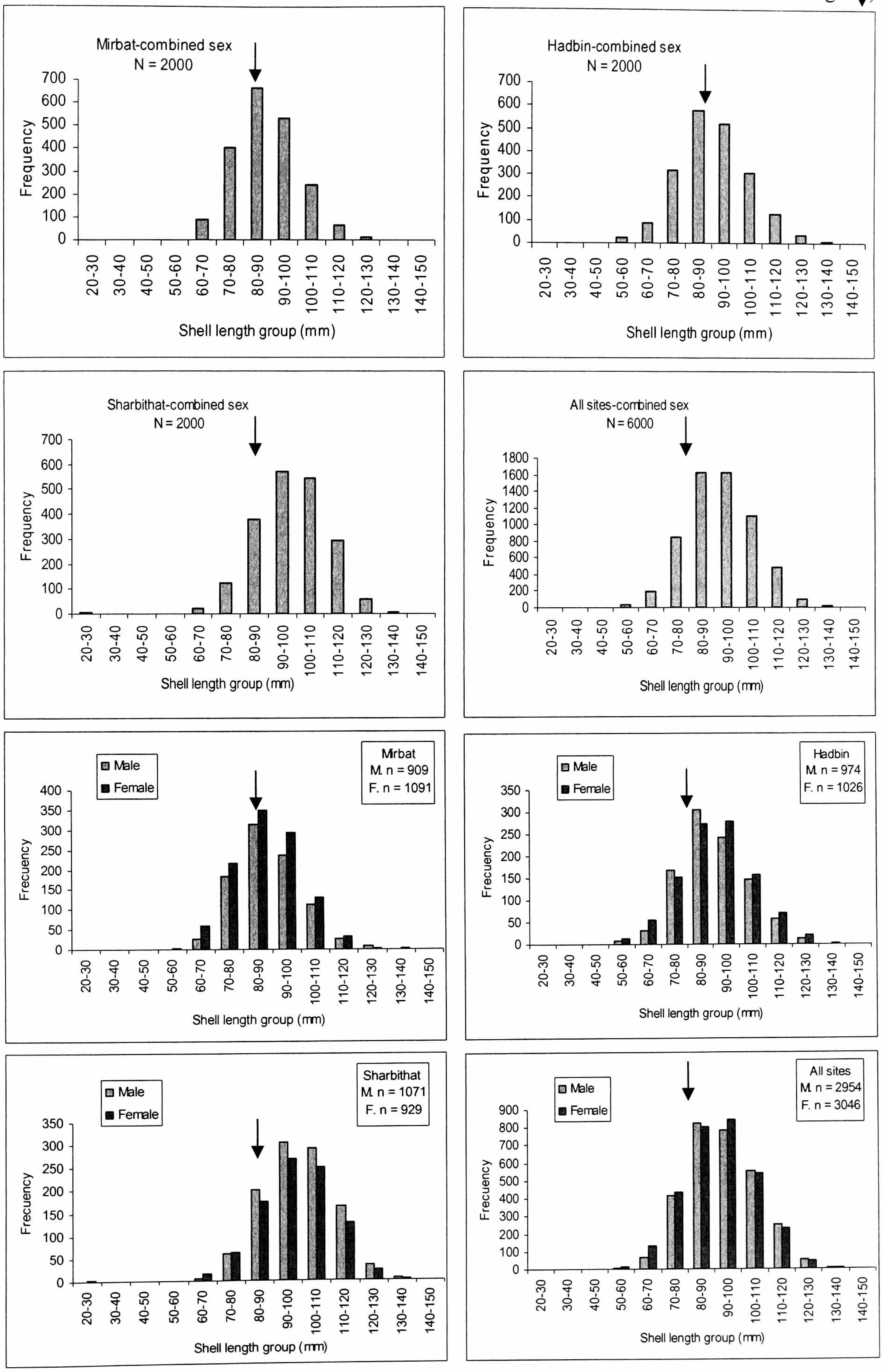
Although size composition of the landings from different depths was similar the size composition of males and females within the landings varied slightly between sites (Figure 3.6).

The divers' landings at the three sites showed a high ratio of small, illegal sizes. The sex ratio of *Haliotis mariae* within the divers' landings was 1:1 for both legal and illegal sized animals (Table 3.3).

Table 3.3 The sex distribution within a sample (n = 2000) of the divers' landing during the fishing season 2003 at the main landing sites.

Landing site	Sample size	Sex ratio		% of Sex ratio	
		Male	Female	Male	Female
Mirbat	2000	909	1091	45.45	54.55
Hadbin	2000	974	1026	48.70	51.30
Sharbithat	2000	1071	929	53.55	46.45
All Sites	6000	2954	3046	49.23	50.77

Figure 3.6 Length-frequency distributions for combined sex, male & female of *Haliotis mariae* in a sample of divers' landing (N=2000) during the fishing season 2003 at three main landing sites: Mirbat, Hadbin and Sharbithat, and for all the sites. (Minimum Legal Size = 90 mm shell length ↓).



3.3.3 Morphometry

The size of monthly sampled *Haliotis mariae* ranged from 46.6 to 138.2 mm in shell length, and from 11.2 to 415.8 g in weight. The biggest animal sampled was a male from Sharbithat station, 138.2 mm in length and 415.8 g in weight (Table 3.4). The overall mean lengths and weights of male and female abalone sampled were 87.6 and 87.7 mm, and 65.2 and 65.5 g, respectively.

Table 3.4 The range of morphological measurements of *H. mariae* sampled between April 2003 and March 2005.

Parameters	Mirbat		Hadbin		Sharbithat	
	Males	Females	Males	Females	Males	Females
Shell length (mm)	47.5 - 120.6	46.6 - 122	49.7 - 130.7	51.9 - 133.5	49.8 - 138.2	53.8 - 126.2
Shell width (mm)	23 - 93.3	32.7 - 100.9	34.4 - 99.1	36 - 104.8	35.9 - 114.4	38.2 - 141.7
Whole weight (g)	12.1 - 249.1	11.8 - 336.3	11.4 - 318.5	16.2 - 367.5	11.2 - 415.8	16.2 - 297.9
Soft body weight (g)	7.1 - 175.1	7.8 - 244.3	7.5 - 202	10.9 - 250.5	6.9 - 263.7	8.7 - 206.5
Foot muscle weight(g)	3.9 - 120.6	4.4 - 155.2	3.7 - 147.3	5.8 - 178.8	3.6 - 163.6	4.6 - 134
Shell weight (g)	4.5 - 124.6	4.0 - 99.2	3.9 - 120.2	5.2 -117	4.3 - 152.1	7.5 - 124.4

The relationships between shell length, as the independent variable, and other variables are summarized in Tables 3.5, 3.6 and 3.7: High r^2 values indicate excellent goodness of fit of linear regression models (see tables).

The following relationships were derived

Whole weight (TW) to shell length (SL) $(TW) = a\,(SL)^b$

Flesh weight (FW) to shell length (SL) $(FW) = a\,(SL)^b$

Shell weight (SW) to shell length (SL) $(SW) = a\,(SL)^b$

Table 3.5 Relationship between log shell length and log whole weight for *Haliotis mariae* at the three sites. a and b are constants in the equation whole weight = *a* (shell length)^b. r^2 = coefficient of determination, *n* = sample size.

Sites	a	b	r^2	*n*
Mirbat	- 4.5058	3.3135	0.9666	1171
Hadbin	- 4.4919	3.3012	0.95	1200
Sharbithat	- 4.3566	3.2315	0.9484	842

Table 3.6 Relationship between log shell length and log flesh weight for *Haliotis mariae* at the three sites. a and b are constants in the equation Flesh weight = *a* (shell length)^b. r^2 = coefficient of determination, *n* = sample size.

Sites	a	b	r^2	*n*
Mirbat	- 5.3824	3.5426	0.9147	1171
Hadbin	- 5.248	3.4717	0.8606	1200
Sharbithat	- 5.226	3.457	0.872	842

Table 3.7 Relationship between log shell length and log shell weight for *Haliotis mariae* at the three sites. a and b are constants in the equation Shell weight = *a* (shell length)^b. r^2 = coefficient of determination, *n* = sample size.

Sites	a	b	r^2	*n*
Mirbat	- 4.4486	3.0477	0.9257	1171
Hadbin	- 4.8322	3.2439	0.9016	1200
Sharbithat	- 4.4409	3.0587	0.8938	842

The morphometrics of *H. mariae* varied within and among the studied populations. ANOVA analysis showed significant difference between the mean of all the different morphometric parameters (shell length, shell width, total weight, flesh weight and shell weight) ($P<0.05$) at different sites. All were higher at Sharbithat compared with Hadbin and Mirbat respectively. With reference to sex, there was significant difference between males and females in the mean shell length, shell width, total weight and the flesh weight ($P<0.05$); females showed higher mean-values. The mean shell length in Sharbithat exceeded the mean shell length in Mirbat and Hadbin. The abalone populations in Mirbat and Hadbin had mean shell lengths much less than the minimum legal size of 90 mm for both male and female; 81.5 mm for males and 83.1 mm for females at Mirbat and 82.6 mm for males and 83.9 mm for females at Hadbin. However, at Sharbithat the mean shell length for both sexes was still higher than the minimum legal size: 98.7 mm for males and 96.1 mm for females (Table 3.8).

Table 3.8 The mean of morphological measurements of *H. mariae* sampled from Mirbat, Hadbin, and Sharbithat between April 2003 and March 2005.

Parameters	Mirbat		Hadbin		Sharbithat	
	♂	♀	♂	♀	♂	♀
Shell length (mm)	81.5	83.1	82.6	83.9	98.7	96.1
Shell width (mm)	60.4	61.5	60.8	61.9	74.6	73.1
Whole weight (g)	78.8	78.8	78.3	80.9	135.4	123.1
Soft body weight (g)	51.2	51.3	49.7	52.0	84.7	77.8
Foot muscle weight (g)	30.2	29.5	29.9	31.2	53.8	48.1
Shell weight (g)	27.6	27.5	28.5	29.0	50.7	45.2

Abalone more than 120 mm shell length were apparent in samples from Sharbithat, infrequent in samples from Hadbin, and very few in samples from Mirbat (Figure 3.7). Individuals more than 90 mm shell length (minimum legal size) were relatively frequent in samples from Sharbithat, but less common in samples from Hadbin and Mirbat. The differences in the size composition between the three sites were also reflected in the size composition of the commercial catch from the three populations during the fishing season.

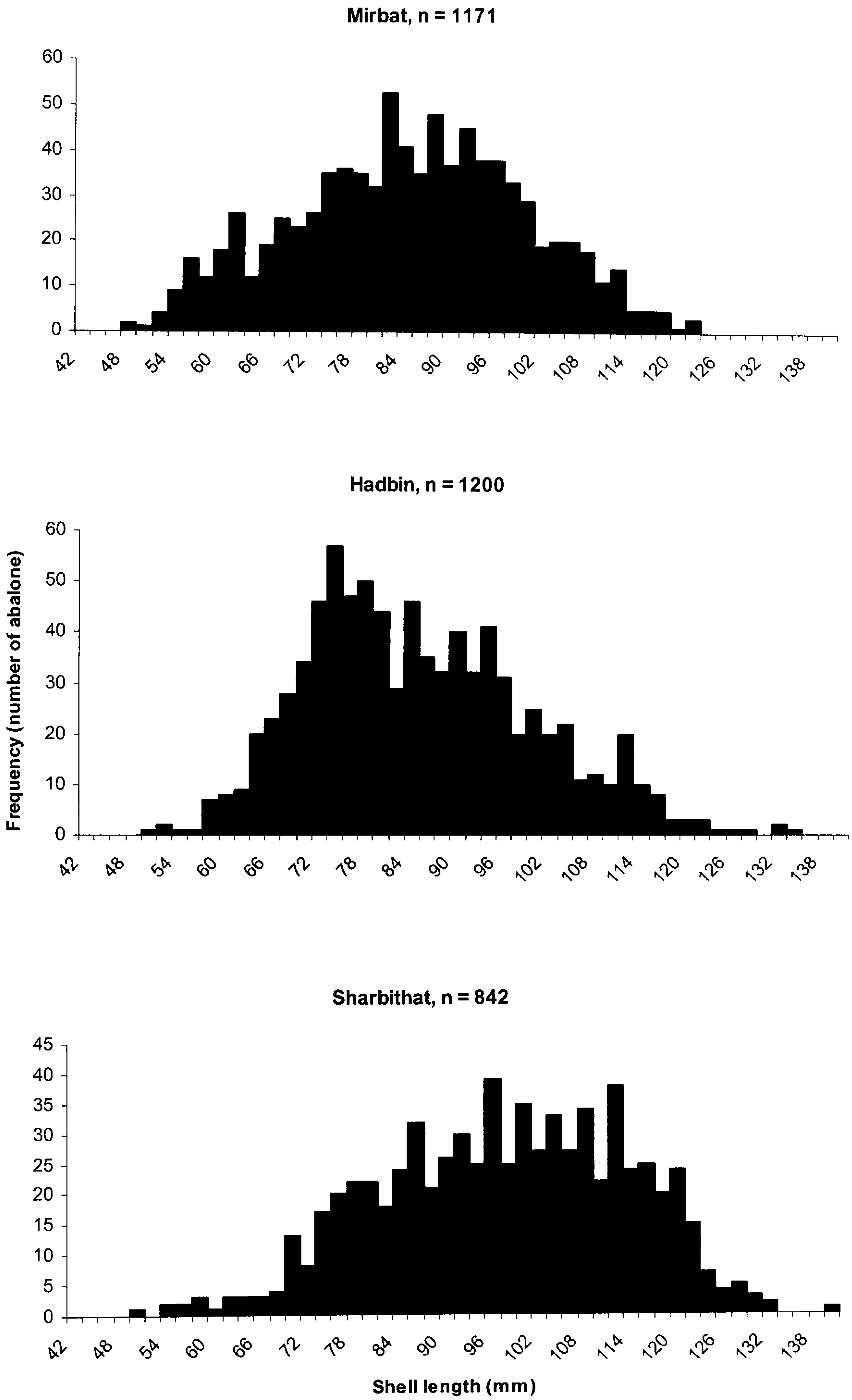


Figure 3.7 Comparison of the length frequency distribution of shells of *H. mariae* sampled from the three study sites for a period of 24 months of the study, n = number of samples in each site (minimum legal size = 90 mm SL).

3.3.4 Size composition of samples (Length frequency)

The size composition of monthly samples depends on the sampling location within a study sites and reflects the size composition of natural populations in that area.

The monthly samples during June, July and August at Mirbat and Hadbin were collected from relatively less-depth protected bays due to rough sea associated with the monsoon season. Thus, the relative abundance of adults *Haliotis mariae* during these months were low in relation to juvenile (Figures 3.8 & 3.9). In addition, at Sharbithat sampling was stopped during the same months, as it was impossible to reach the study stations in this area (Figure 3.10).

Monthly size-frequency histograms of *Haliotis mariae* collected from the three sites all had a preponderance of late juveniles and adults; there were very few young animals in the samples < 50 mm SL. This is thought to be due to the cryptic habitat occupied by young juveniles, which live under boulders and small rocks and are inaccessible to divers. It is only when a size of 50-70 mm SL is reached that they begin in occupy cracks and crevices of open rocks, where they are more easily collected (Shepherd, 1973).

The bimonthly size–frequency data failed to show significant temporal or modal progression trends (Figures 3.8, 3.9 and 3.10).

Generally, the relative abundance of adults over the minimum legal size limit (> 90 mm SL) at Mirbat and Hadbin was much less than that at Sharbithat. The scarcity of large sizes and low density are factors, which explain the low recruitment of *Haliotis mariae* during the last years, suggest that, the stock is seriously affected, and require a reduction in the heavy fishing intensity or stop the fishery to conserve the remaining populations.

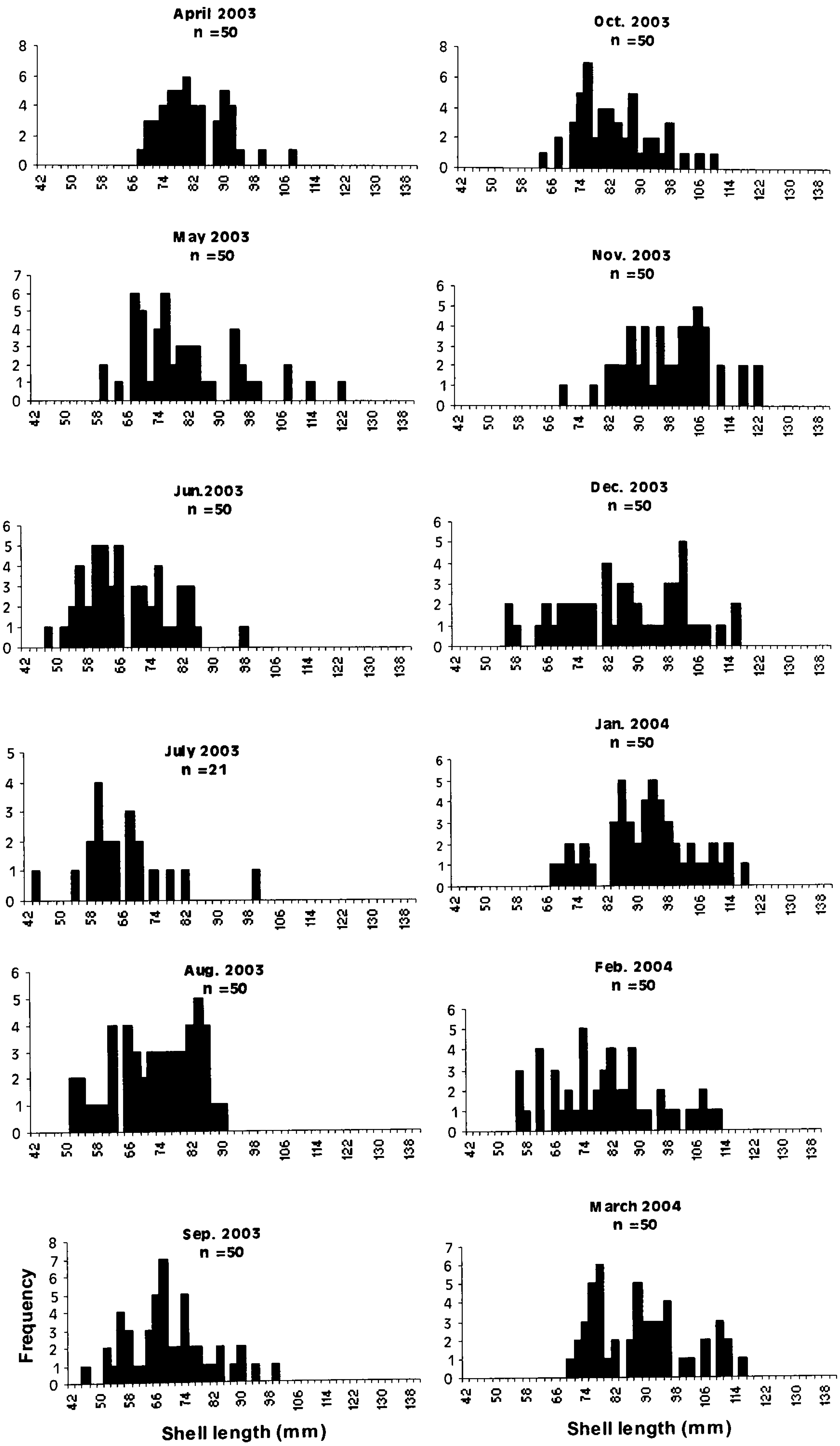
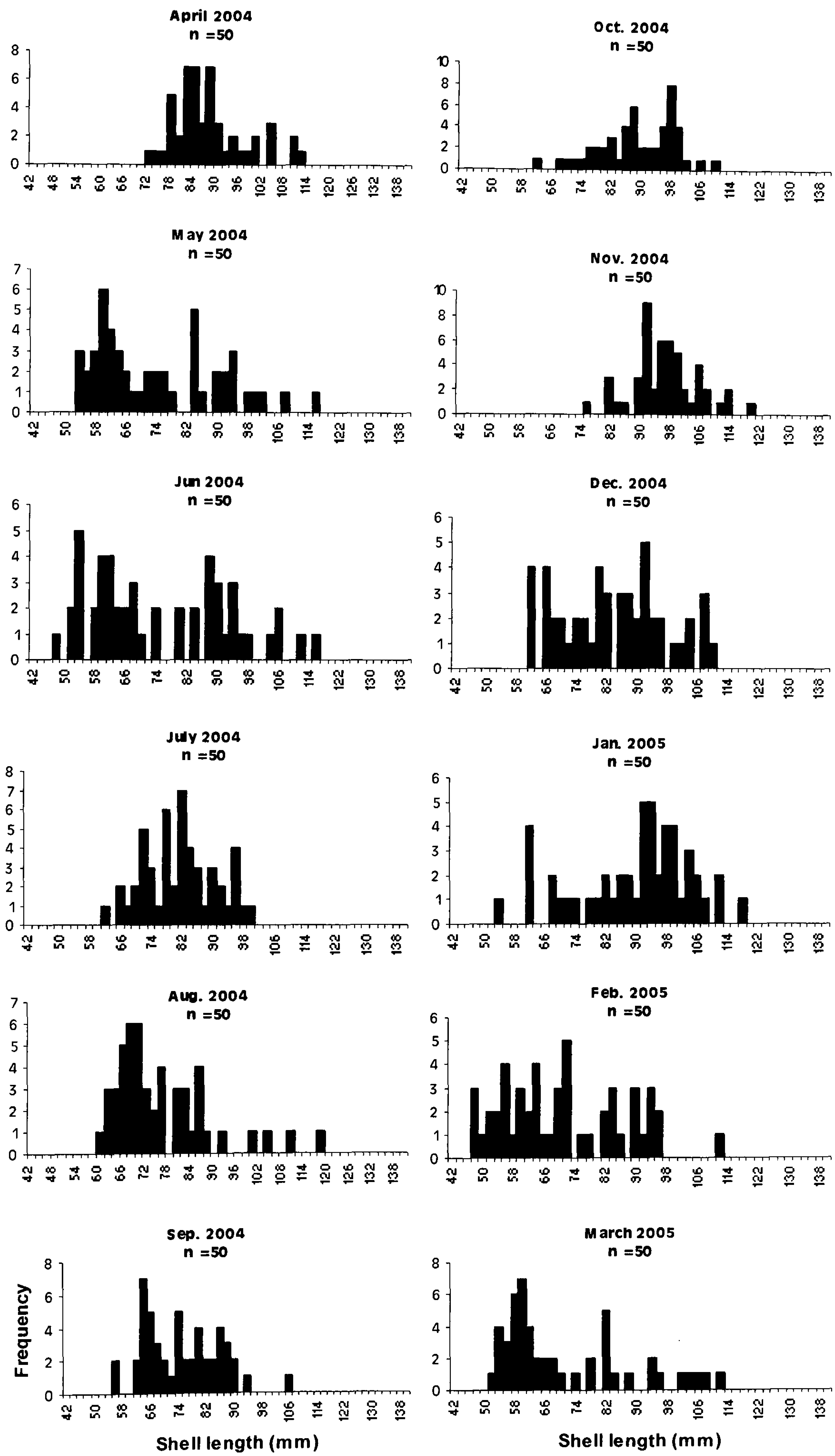


Figure 3.8 Length frequency distribution of abalone sampled from Mirbat station during the first year (April 2003 – March 2004) (MLS = 90 mm SL).



(Figure 3.8 continued), Length frequency distribution of abalone sampled from Mirbat station during the second year (April 2004 – March 2005) (MLS = 90 mm SL).

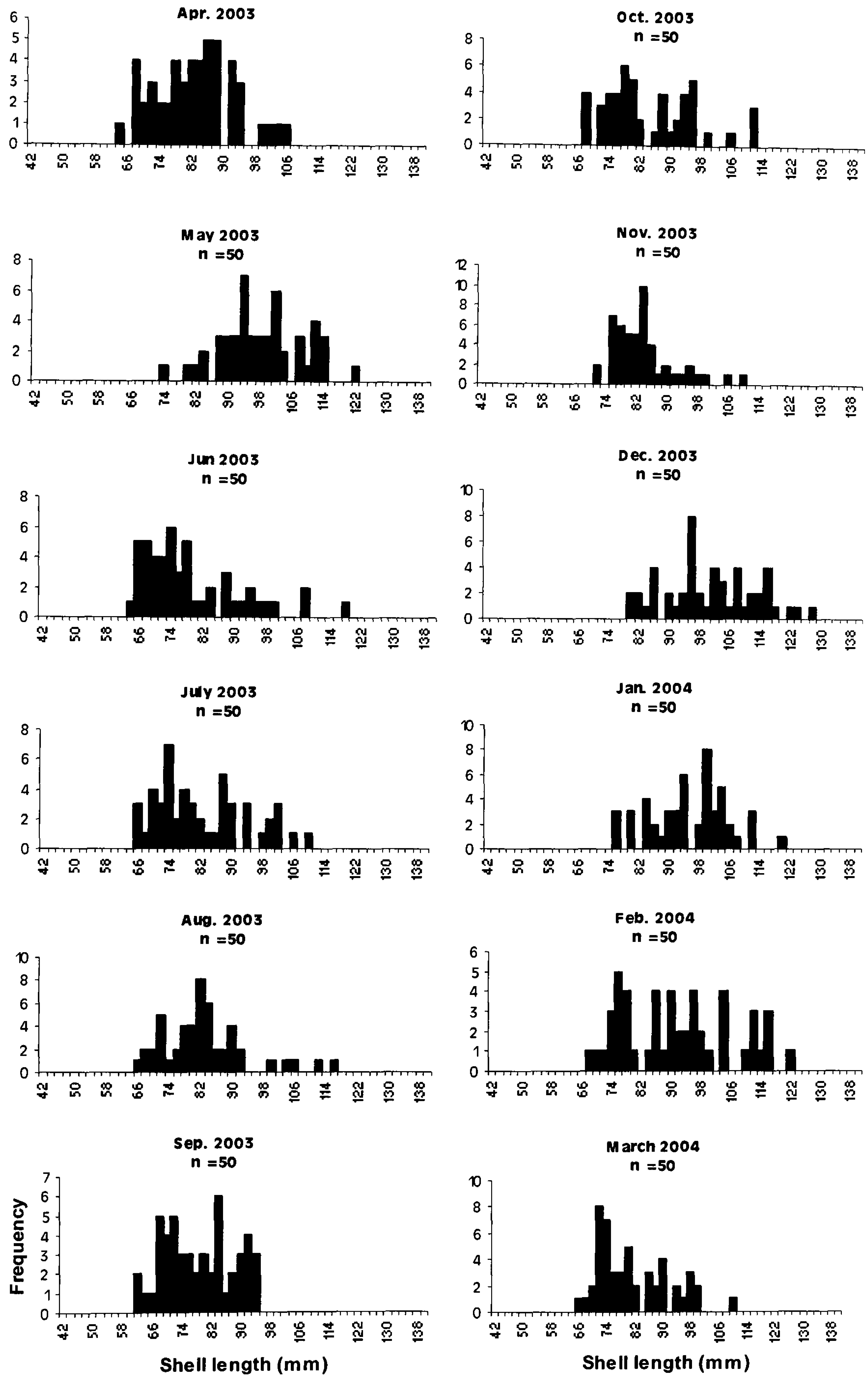
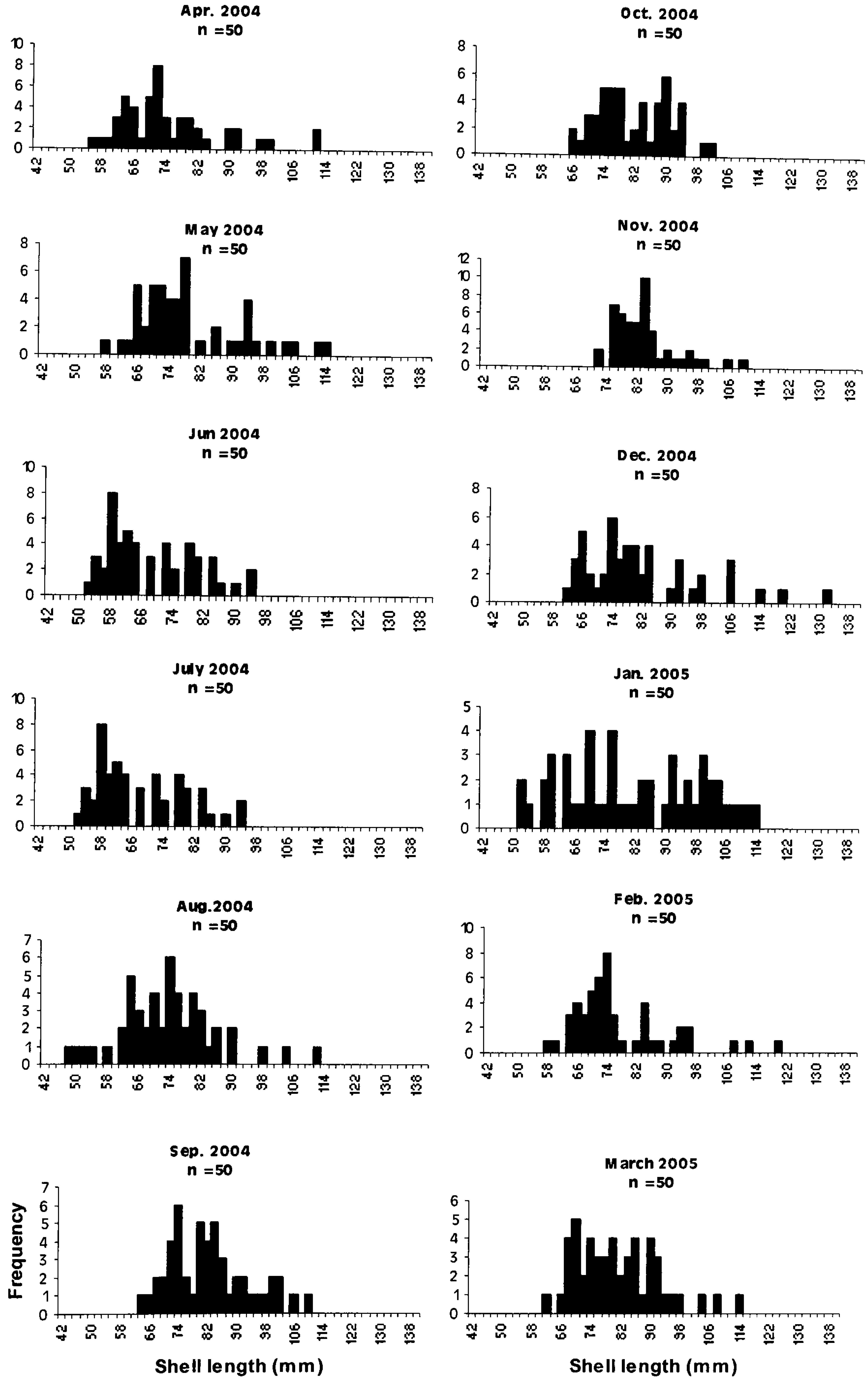


Figure 3.9 Length frequency distribution of abalone sampled from Hadbin station during the first year (April 2003 – March 2004) (MLS = 90 mm SL).



(Figure 3.9 continued) Length frequency distribution of abalone sampled from Hadbin station during the second year (April 2004 – March 2005) (MLS = 90 mm SL).

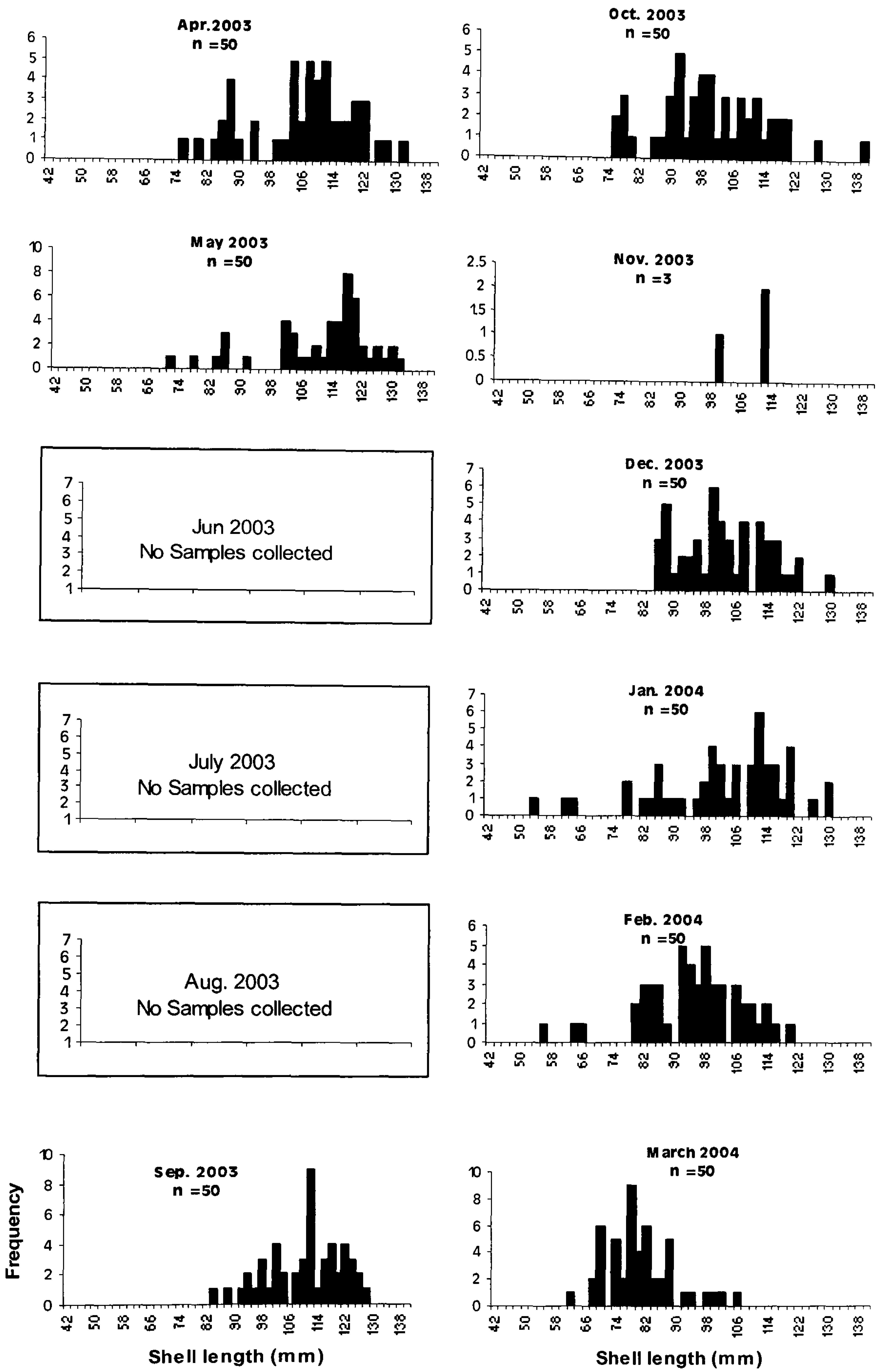
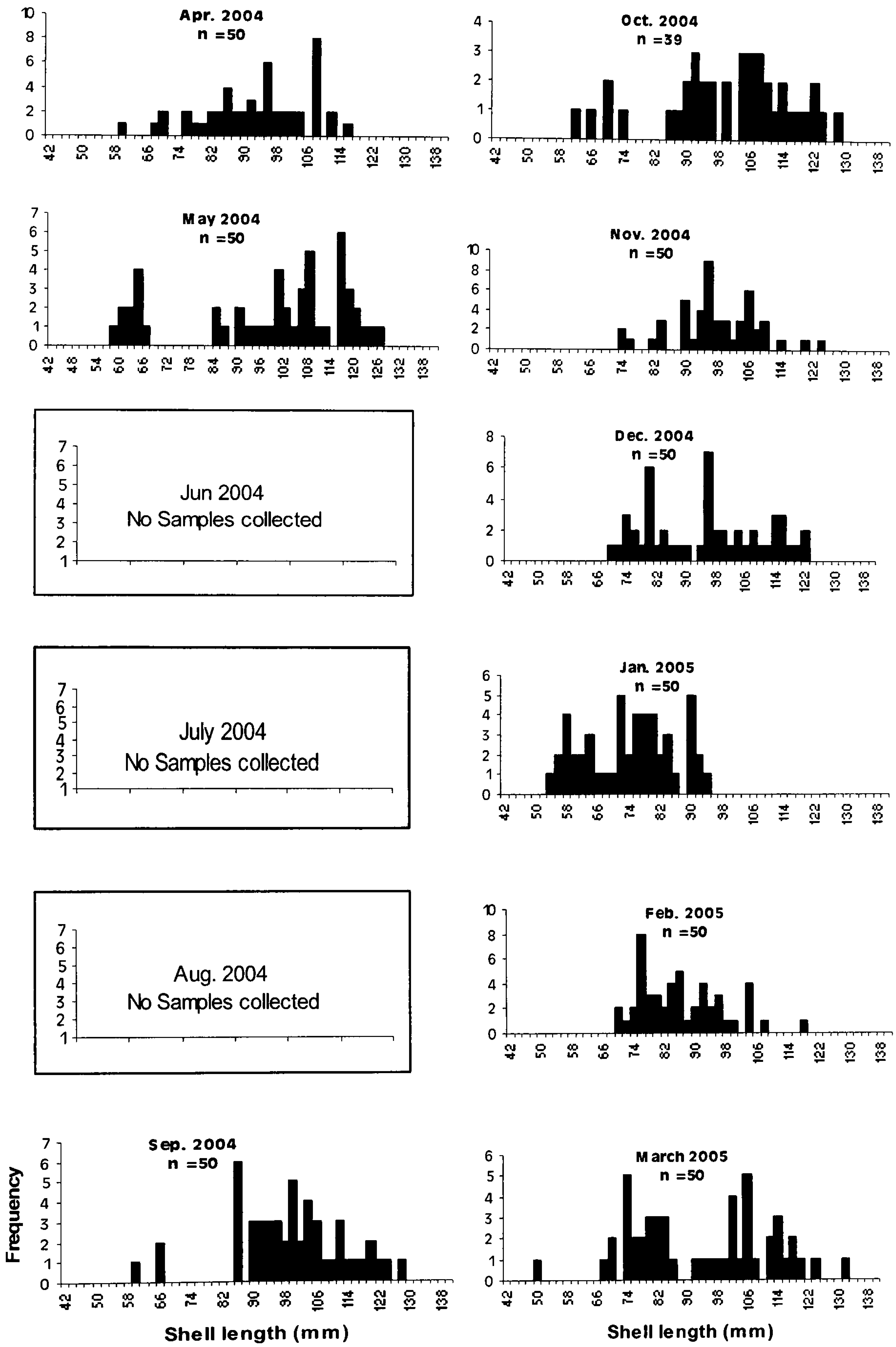


Figure 3.10 Length frequency distribution of abalone sampled from Sharbithat station during the first year (April 2003 – March 2004) (MLS = 90 mm SL).



(Figure 3.10 continued) Length frequency distribution of abalone sampled from Sharbithat station during the second year (April 2004 – March 2005) (MLS=90 mm SL).

3.3.5 Sex ratio

A total of 3213 abalone were examined during the study. There were 1171 from Mirbat, 1200 from Hadbin, and 842 from Sharbithat. No significant differences in sex ratio were found between sites (Chi-Square Test: $P > 0.05$). In all areas, the sex ratio between male and female approximated 55% male 45% female (Table 3.9).

Table 3.9 Distribution of sexes of *Haliotis mariae*, April 2003 – March 2005

	Number			Ratio		
Sites	♂	♀	undefined	♂	♀	undefined
Mirbat	482	367	322	41.2%	31.3%	27.5%
Hadbin	467	370	363	38.9%	30.8%	30.3%
Sharbithat	418	292	132	49.6%	34.7%	15.7%

Sanders (1982) found a 1:1 sex ratio for *H .mariae* from the southern region of Oman but Shepherd *et al.* (1995) reported a greater population of females *Haliotis mariae* 59% for the same fishery. Deviations from the 1:1 sex ratio have been found elsewhere (Shepherd & Laws, 1974; Giorgi & DeMartini, 1977; Shepherd, 1987; Wells & Keesing, 1989; Shepherd *et al.*, 1991).

Differences were found in the proportion of males to females between sites with months (Figure 3.11). Males were more prevalent during the non upwelling periods and immature abalone were most prolific during the upwelling.

Bolognari (1954) reported a preponderance of males over females for *H. lamellose*, where females tend to be more numerous in populations of older molluscs (Fretter & Graham, 1964, Comfort, 1957), but in *H. mariae* the trend is the other way.

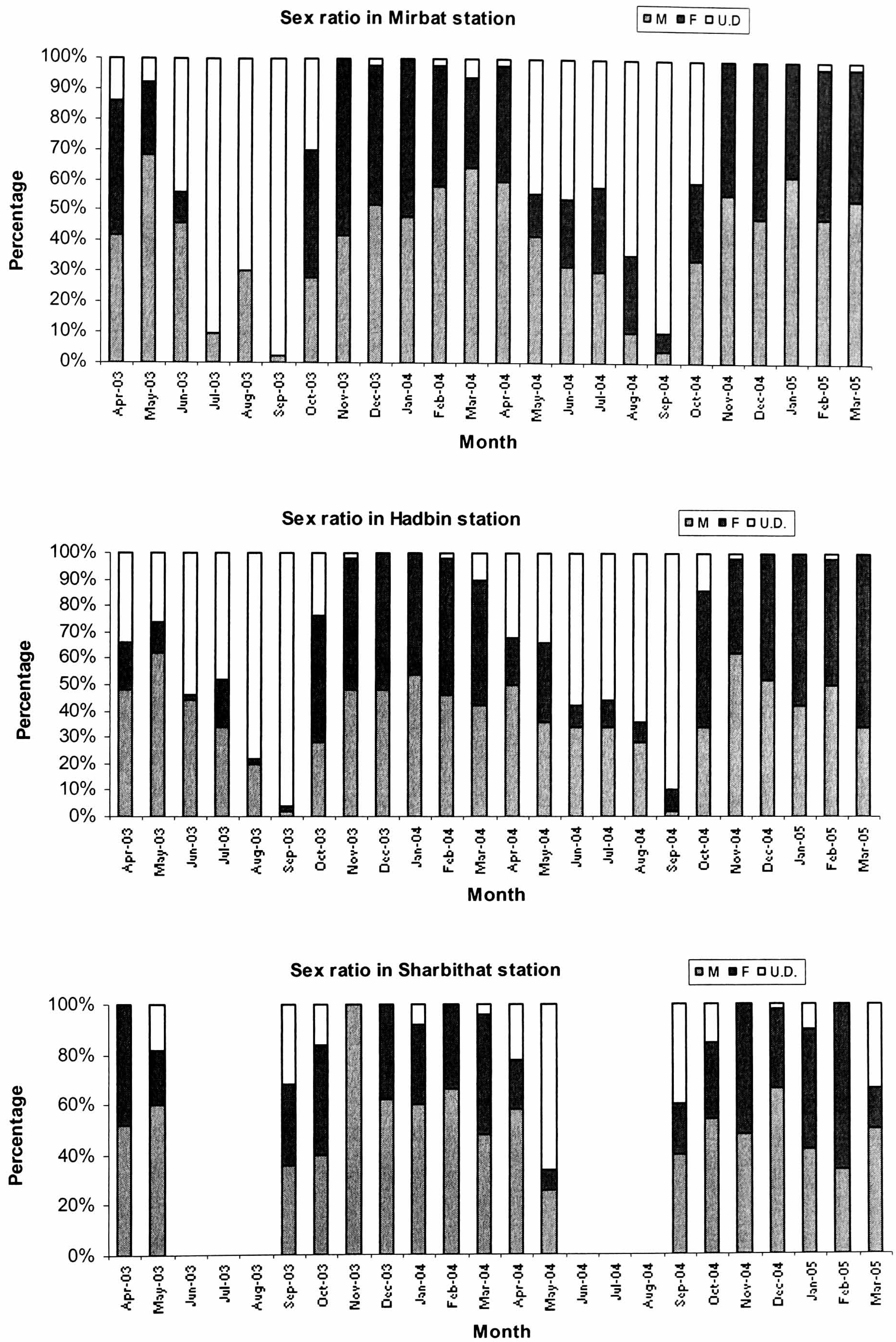


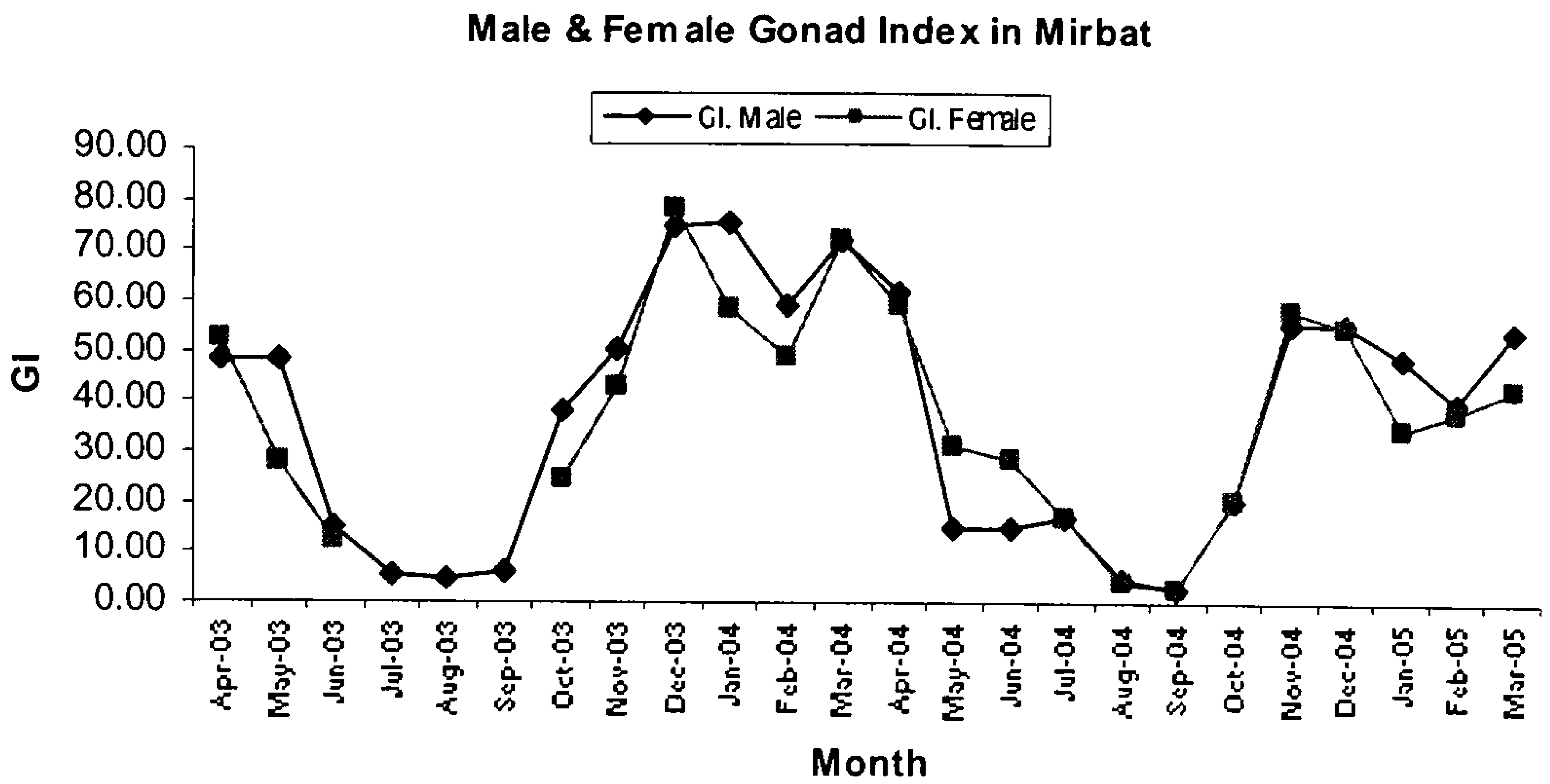
Figure 3.11 Monthly sex ratio distribution at the three stations, Mirbat, Hadbin and Sharbithat, during April 2003 – March 2005. (M: male, F: female, U.D: undefine).

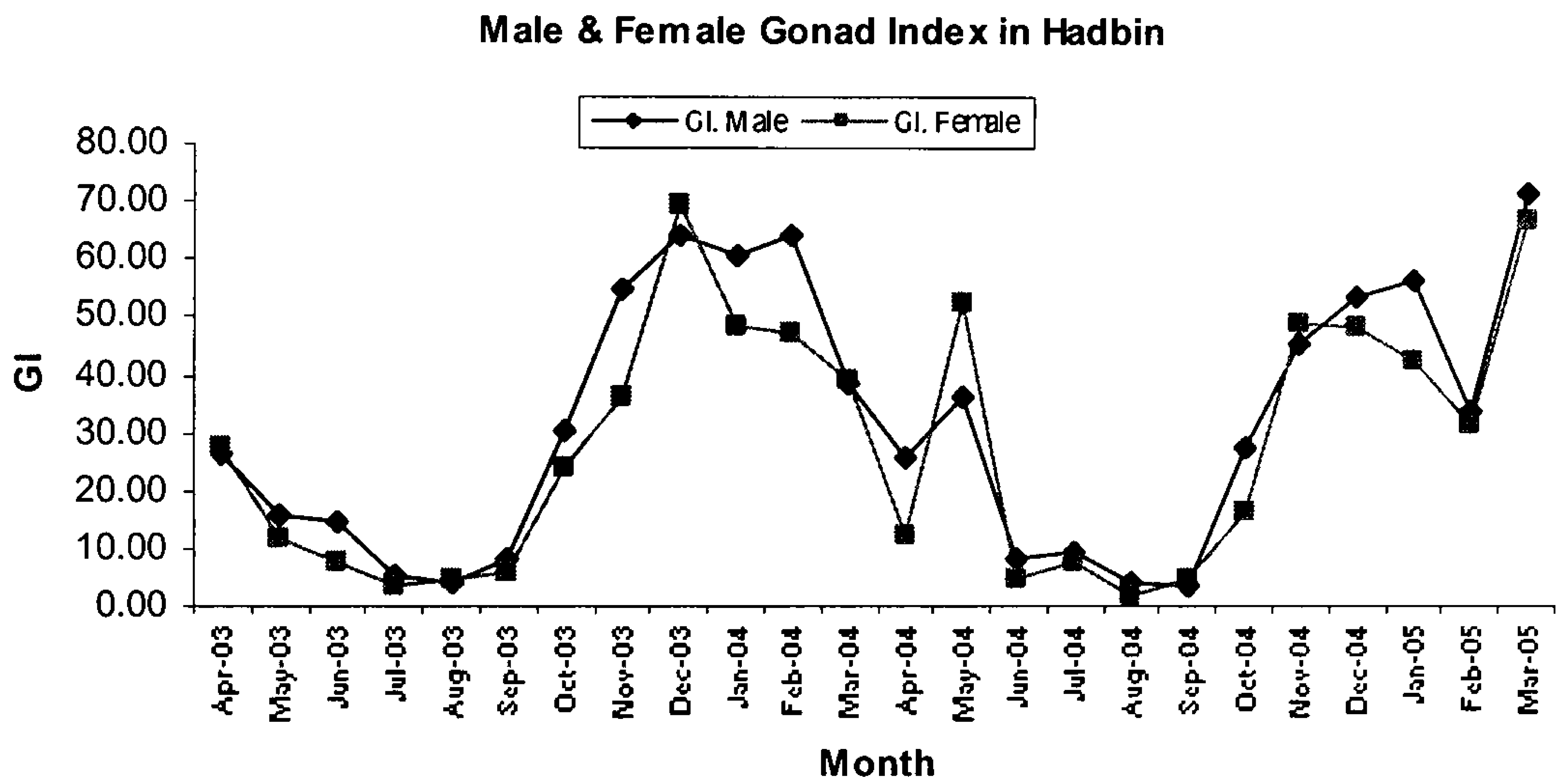
3.3.6 Gonad Index and spawning season

Throughout the study, there were no differences between Gonad Index of males and females sampled in the same month (Figure 3.12). There were significant increases in Gonad Index of both sexes from September to December.

The gonads enter a period of growth beginning in late September, attaining maximum size towards the end of November early December (towards the spawning season). Thereafter, growth declines towards the monsoon season in June and continues until the end of September, at which time the gonads enter a quiescent period (Figure 3.12).

The highest average GI in males at Mirbat was during January 2004 (75.85), but during March 2005 in Hadbin (71.96), and during February 2004 in Sharbithat (73.75). For females, the peak GIs occurred at each site around December each year (Figure 3.12). There was no discernible difference in their trends between locations for both sexes. These data suggest *Haliotis mariae* has a well-defined reproductive period beginning in December and continuing to April.





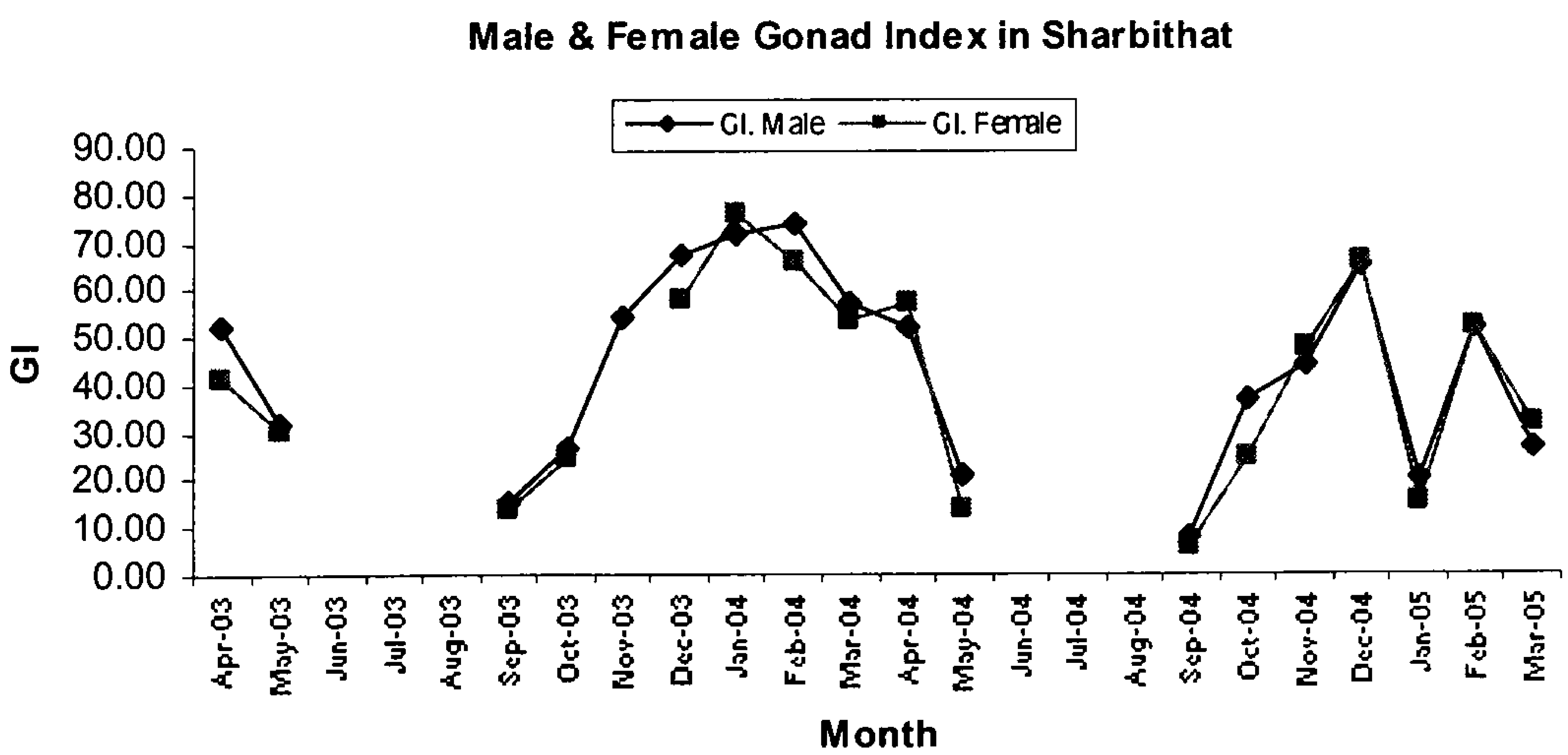


Figure 3.12 Seasonal changes of gonad index of male and female *Haliotis mariae* sampled from three stations at the southern coast of Oman (Mirbat, Hadbin, and Sharbithat) during the period April 2003 – March 2005.

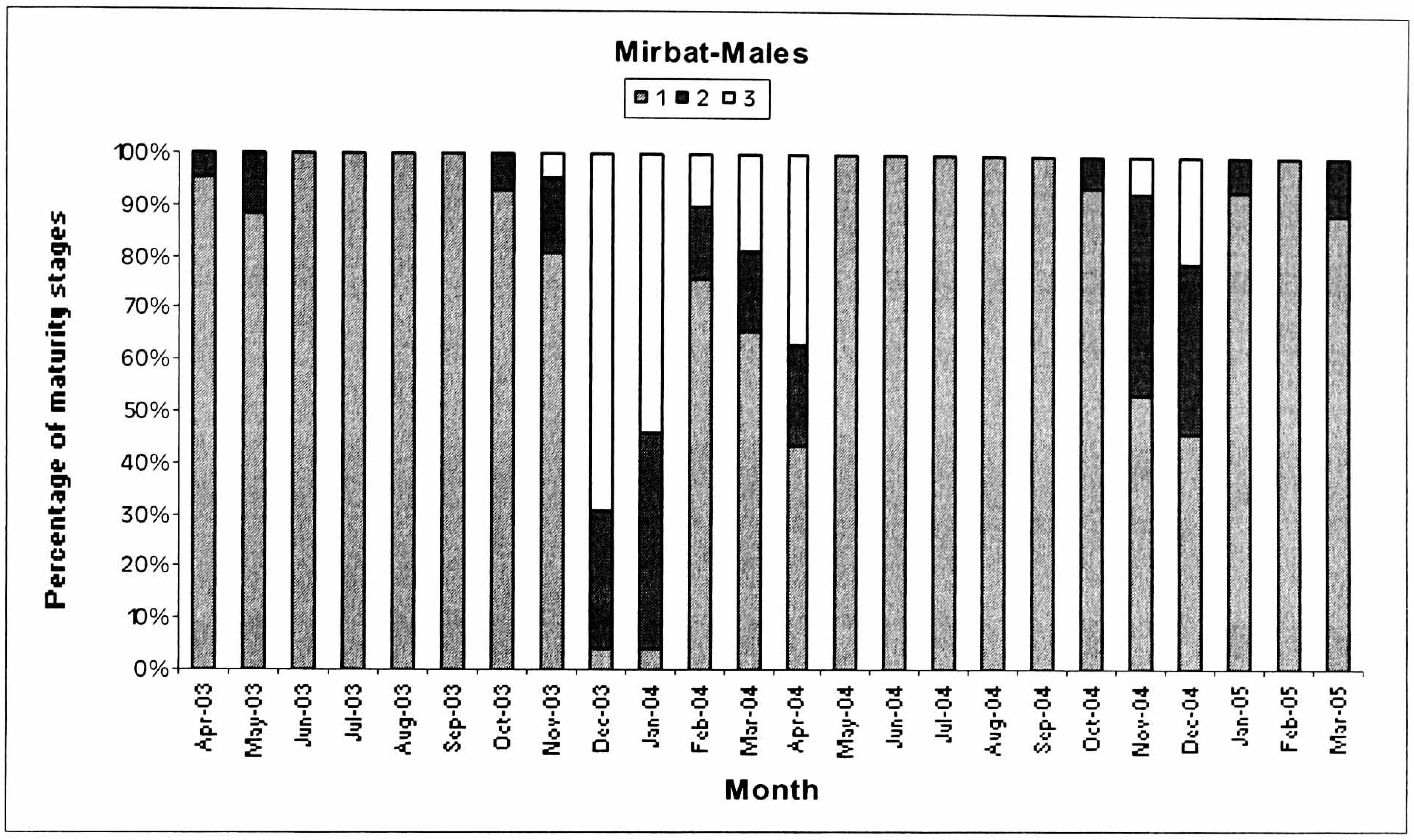
3.3.7 Maturity stages

The sexes in *Haliotis maria* are separate and defined by the presence of gonads colour. The mature female gonad appears dark green in colour whereas the male gonad is creamy white. Gonad maturation generally is affected by availability of food, changes in water temperature, moon phase, daylight, and salinity. The animals reproduce using a process called broadcast spawning, which occurs when all the mature adults of both male and female abalone tend to congregate in the shallow subtidal zone, gathering in relatively high densities in the surrounding area and releasing their sperms and eggs into the water column. This is always associated with a fall in temperature between November and January.

The sexual maturity of *H. mariae* could be classified into four stages: stage zero which represents no development and sex cannot be determined, and three later developmental stages. The observations on maturity and spawning of *H. mariae* at the three study areas are summarized in Figures 3.13, 3.14 and 3.15. Both sexes followed similar patterns in maturation but they varied between sites. At the Mirbat site, the gonads were generally full and ripe between November and April, with a peak in November and December. Immediately after, associated with the temperature fall, a significant fraction of the gonad was spent, thus indicating the main period of spawning. From May onwards, there was no sexual activity and reproductively resting animals started to dominate the population. This trend continued in the following months and the resting animals were present until October when the gonads started to develop again with increased food availability associated with the monsoon season (Figure 3.13).

At Hadbin, the animals were mature between November and February with a peak in December and February (Figure 3.14). Spawning occurs from December to March in this area with the same trend as at Mirbat region. However, at Sharbithat the period of maturity and spawning appears to be between November and March with a peak in January and February (Figure 3.15). This region is also affected by the monsoon season.

Based on the occurrence of advanced maturity stages, the months from November to April inclusive appear to be the months of spawning at all the three sites. Thus, *H.mariae* spawns once a year during these months. This is corroborated by the gonad index study, together with the results of previous studies (Sander, 1982; Savidge *et al.*, 1986; Siddeek *et al.*, 1993; Shepherd *et al.*, 1995; Ogawa 1997).



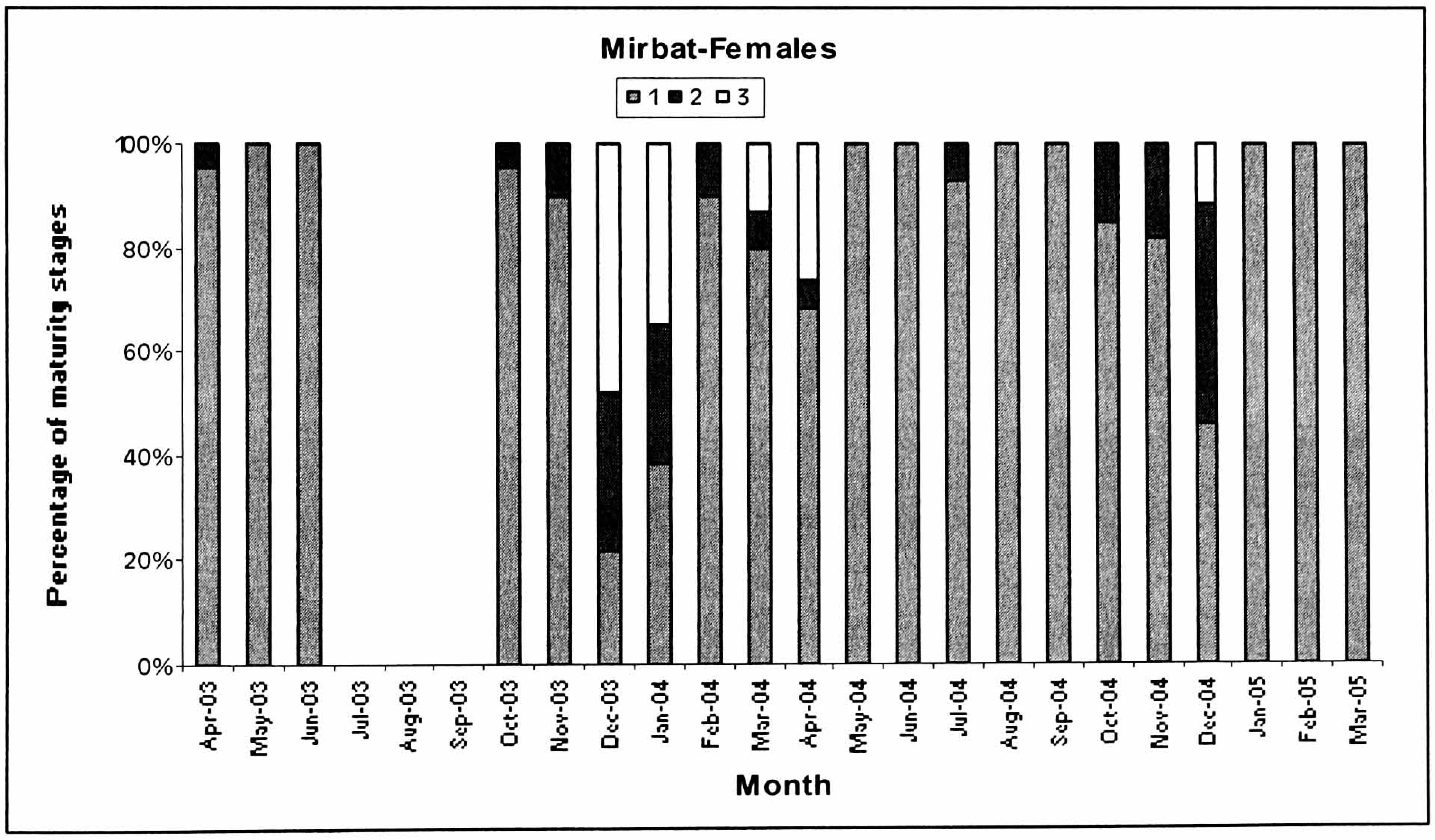
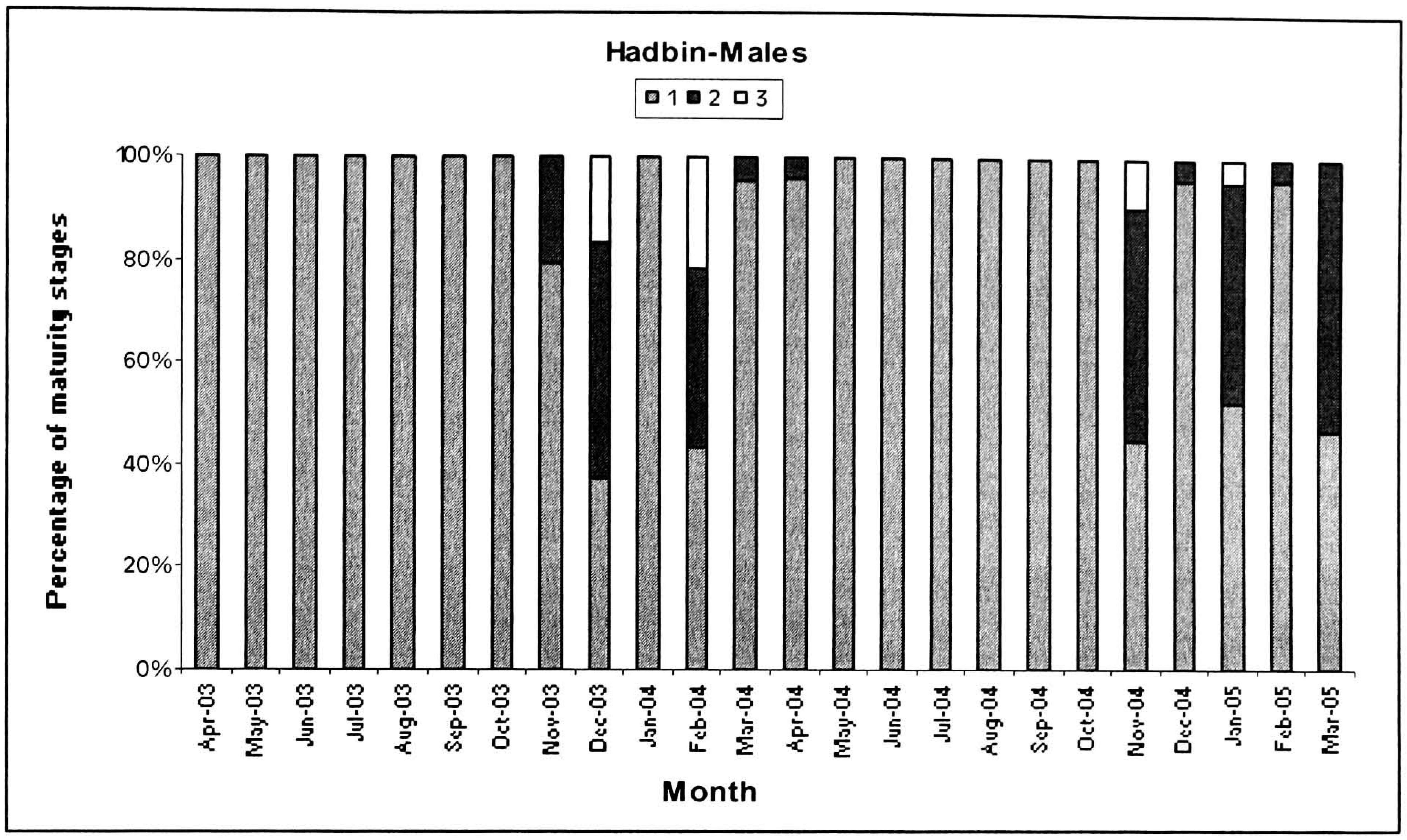


Figure 3.13 Percentage of males and females in relation to their maturity stages in Mirbat station between April 2003 and March 2005. (stage 1 is when the sexes can be distinguished and the gonad starts to develop below the shell periphery; stage 2 is when the gonad is slightly developed to reach the level of the shell periphery; and stage 3 is when the gonad is well developed, expanding beyond the shell periphery. The annual reproductive cycle of *H. mariae* was confirmed through percentage frequencies of different gonad maturity stages.



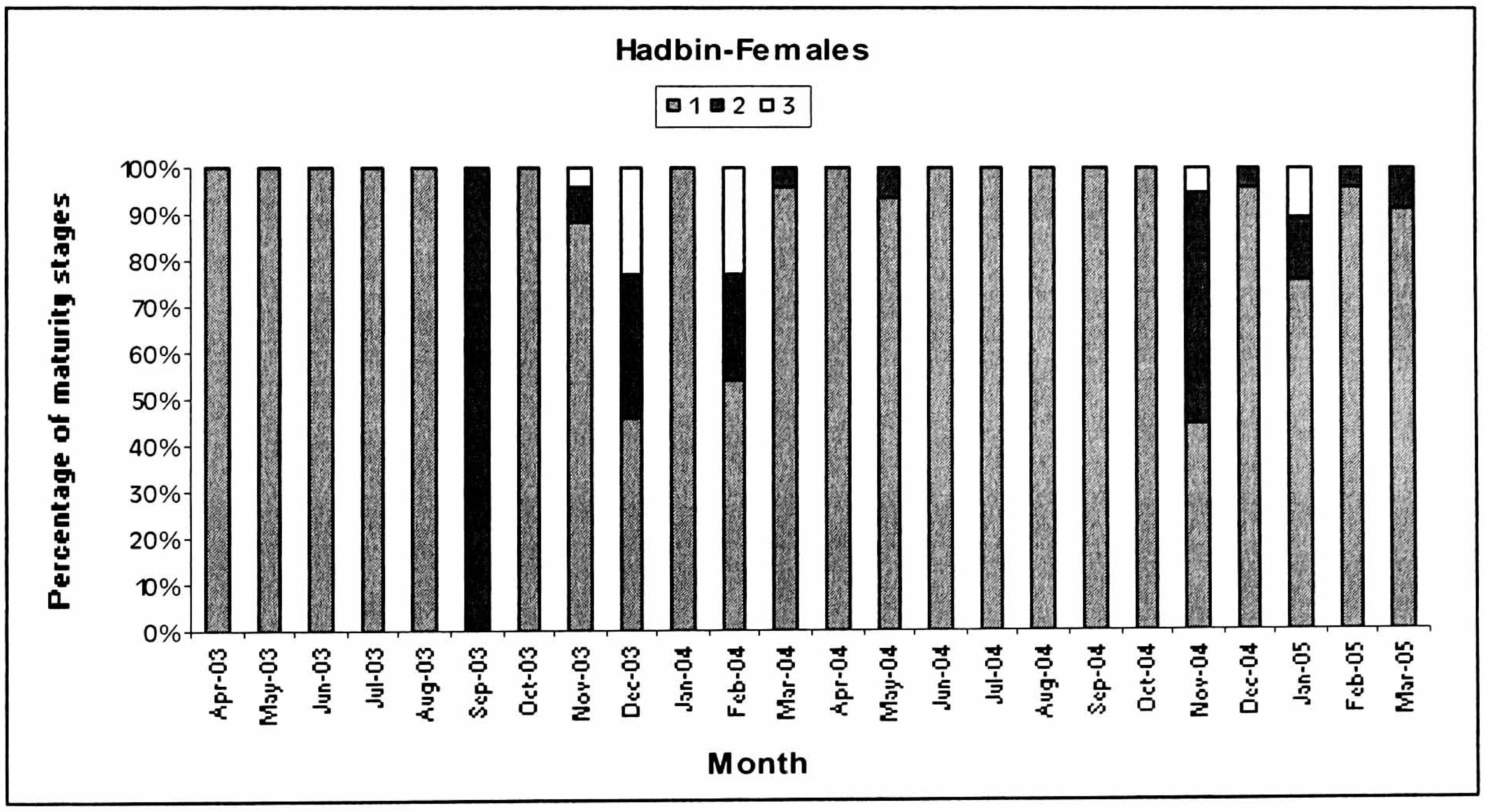
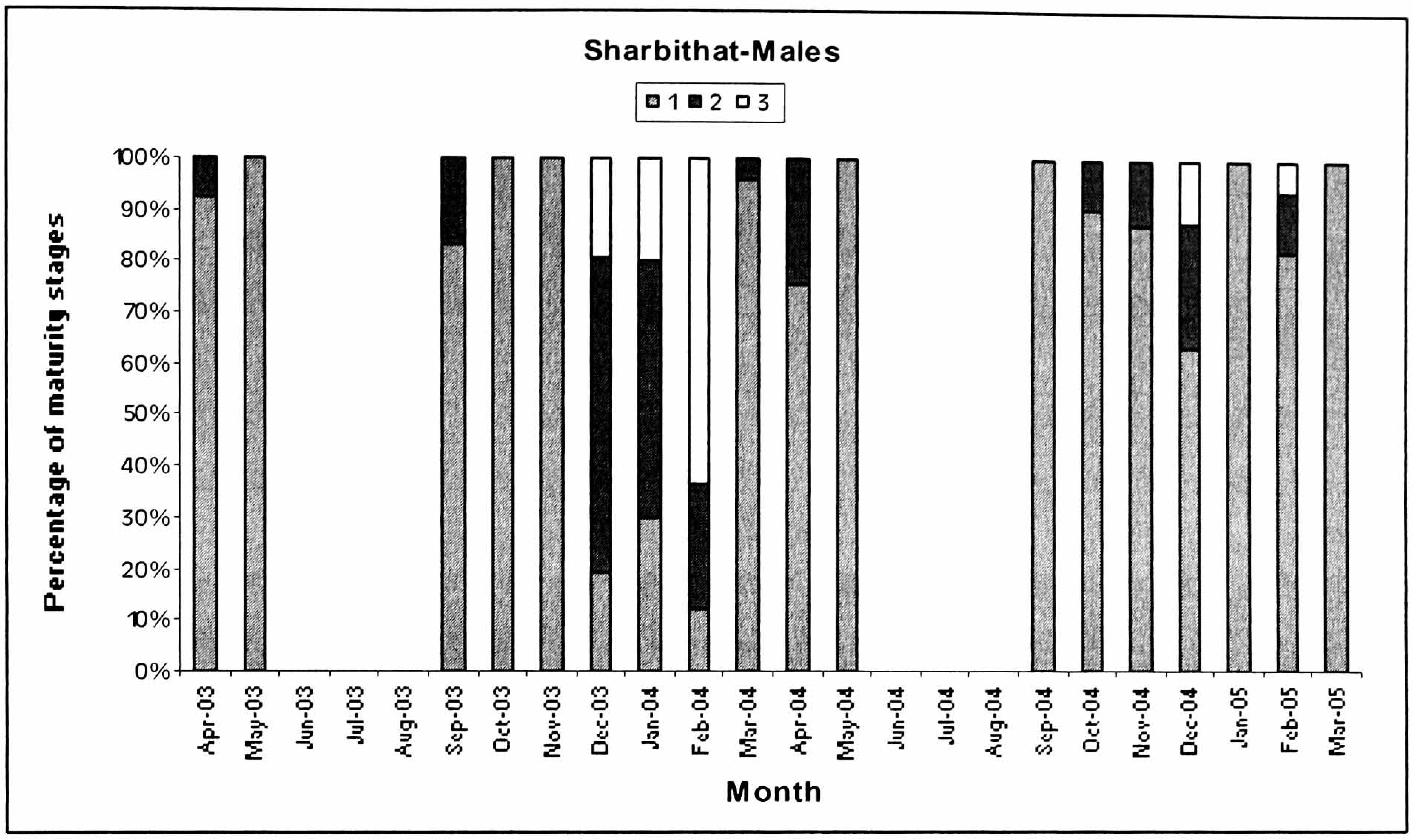


Figure 3.14 Percentage of males and females in relation to their maturity stages in Hadbin station between April 2003 and March 2005. (stage 1 is when the sexes can be distinguished and the gonad starts to develop below the shell periphery; stage 2 is when the gonad is slightly developed to reach the level of the shell periphery; and stage 3 is when the gonad is well developed, expanding beyond the shell periphery. The annual reproductive cycle of *H. mariae* was confirmed through percentage frequencies of different gonad maturity stages.



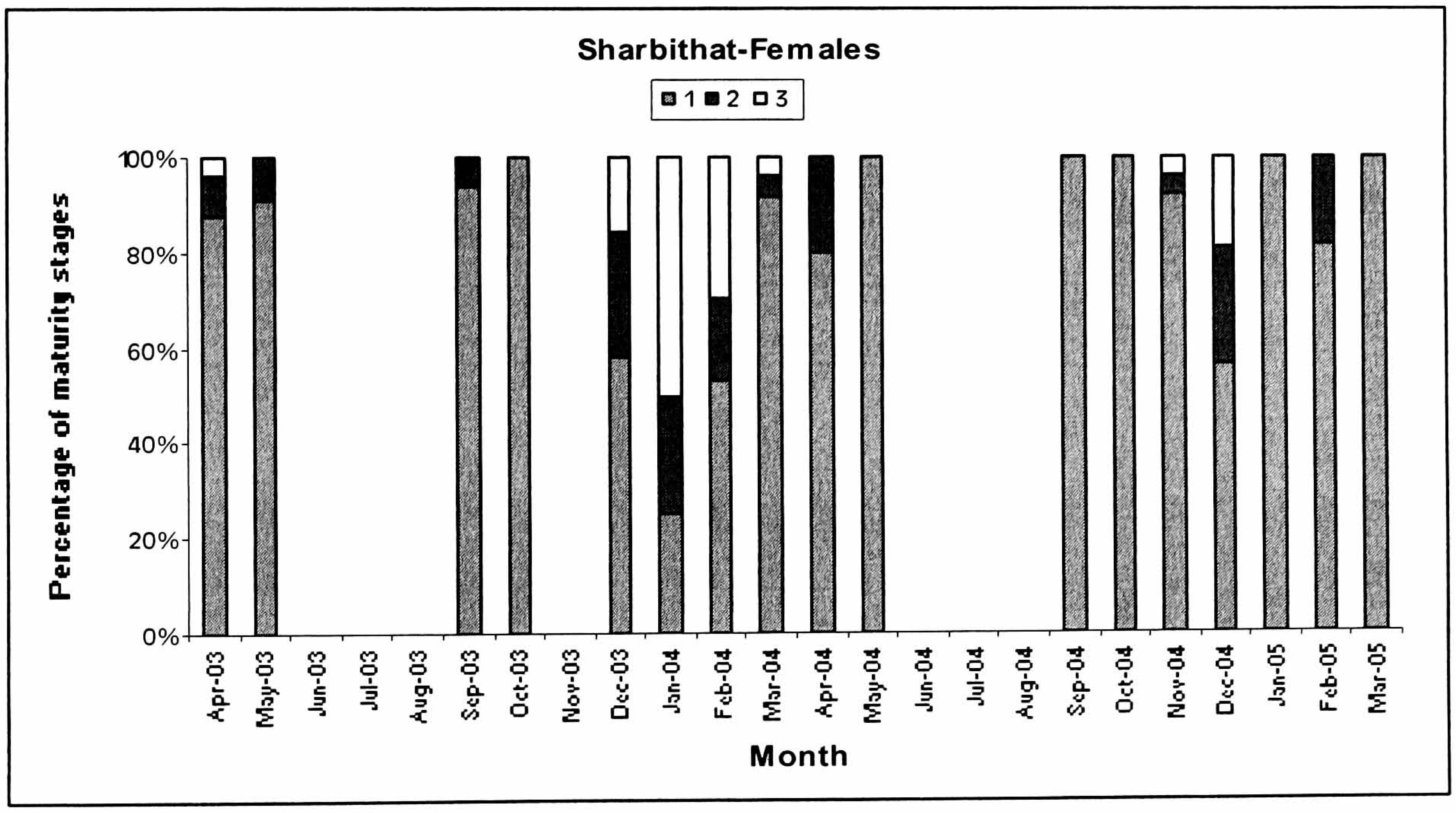


Figure 3.15 Percentage of males and females in relation to their maturity stages in Sharbithat station between April 2003 and March 2005. (stage 1 is when the sexes can be distinguished and the gonad starts to develop below the shell periphery; stage 2 is when the gonad is slightly developed to reach the level of the shell periphery; and stage 3 is when the gonad is well developed, expanding beyond the shell periphery. The annual reproductive cycle of *H. mariae* was confirmed through percentage frequencies of different gonad maturity stages.

3.3.8 Size at first maturity

Sexual maturity for male and female *Haliotis mariae* at Mirbat occurred between 60-120 mm SL and 60-110 mm SL respectively (Table 3.10). At Hadbin, it was between 60-120 mm SL and 60-130 mm SL for males and females respectively, whereas at Sharbithat it was between 70-120 mm SL for both sexes.

Table 3.10 Occurence of advance sexually stages at different size and the percentage and accumulated percentage of maturity stage for male and female abalone *Haliotis mariae* from three stations (Mirbat-Hadbin-Sharbithat respectivily) sampled between April 2003 and March 2005.

Length group (mm)	Total number of sample		Numbers ripe (at stage 3)		Percentage ripe (% at stage 3)		Accumulated % ripe (% at stage 3)	
	♂	♀	♂	♀	♂	♀	♂	♀
40 – 49.9	1	2	0	0	0	0	0	0
50 – 59.9	39	18	0	0	0	0	0	0
60 – 69.9	61	42	2	2	3.4	6.7	3.4	6.7
70 – 79.9	97	71	15	9	25.4	30.0	28.8	36.7
80 – 89.9	106	106	11	13	18.6	43.3	47.4	80
90 – 99.9	100	83	17	5	28.8	16.7	76.2	96.7
100 – 109.9	53	35	13	1	22.1	3.3	98.3	100
110 – 119.9	24	8	1	0	1.7	0	100	100
120 – 129.9	1	2	0	0	0	0	100	100
130 – 139.9	0	0	0	0	0	0	100	100

Length group (mm)	Total number of sample		Numbers ripe (at stage 3)		Percentage ripe (% at stage 3)		Accumulated % ripe (% at stage 3)	
	♂	♀	♂	♀	♂	♀	♂	♀
40 – 49.9	1	0	0	0	0	0	0	0
50 – 59.9	14	5	0	0	0	0	0	0
60 – 69.9	69	43	2	2	15.4	11.8	15.4	11.8
70 – 79.9	129	114	0	1	0	5.9	15.4	17.7
80 – 89.9	90	91	4	2	30.8	11.8	46.2	29.5
90 – 99.9	89	63	5	3	38.4	17.6	84.6	47.1
100 – 109.9	44	32	1	2	7.7	11.7	92.3	58.8
110 – 119.9	27	17	1	6	7.7	35.3	100	94.1
120 – 129.9	3	3	0	1	0	5.9	100	100
130 – 139.9	1	2	0	0	0	0	100	100

Length group (mm)	Total number of sample		Numbers ripe (at stage 3)		Percentage ripe (% at stage 3)		Accumulated % ripe (% at stage 3)	
	♂	♀	♂	♀	♂	♀	♂	♀
40 – 49.9	1	0	0	0	0	0	0	0
50 – 59.9	3	5	0	0	0	0	0	0
60 – 69.9	13	9	0	0	0	0	0	0
70 – 79.9	4	50	5	3	13.2	13.6	13.2	13.6
80 – 89.9	68	51	7	5	18.4	22.7	31.6	36.3
90 – 99.9	85	68	12	7	31.6	31.8	63.2	68.1
100 – 109.9	85	59	7	5	18.4	22.7	81.6	90.8
110 – 119.9	94	38	7	2	18.4	9.2	100	100
120 – 129.9	23	12	0	0	0	0	100	100
130 – 139.9	3	0	0	0	0	0	100	100

3.3.9 Growth estimation

A total of 50 tagged abalone of the 197 released samples were recovered after one year (30 live animals & 20 dead shells), and of the 37 tagged abalone in the tank, 33 survived. The recovered percentage of tagged released samples was 15% live animals, plus 10% dead shells, which were found by research divers, scattered over the seabed (Table 3.11).

Table 3.11 Number of tagged *Haliotis mariae* released and recovered from the wild, and number of samples reared in tanks for a period of one year (April 2004-Aprile2005).

	Number of abalone			
Samples	Tagged	Recaptured	% recaptured	Days at liberty
Released tagged samples	197	30	15%	364
Tank samples	37	33	89%	380

Most of the recovered tagged abalone had positive length increments, few individuals of the tank tagged abalone had negative increments. Preliminary analyses of the tagged abalone data suggested that inclusion of negative growth increments would impact on the values of growth rate derived from the analysis. Thus measurements from dead tagged shells found on the seabed and samples with negative growth increments were excluded because they do not make sense biologically. Negative length increments were recorded only in three samples of the tank tagged abalone and it generally appeared to be the result of measurement error (the negative increments represented length reductions of less than 2 mm).

The mean shell length and total weight for the released tagged samples at marking was 56.8 mm and 22.8 g respectively, whereas the mean shell length at recapture was 65.5 mm and mean total weight was 28 g after 364 days at liberty. The mean annual incremental growth rate was 8.7 mm, with 5.2 g increment in weight.

For the reared samples, the mean shell length and total weight at marking was 61.4 mm and 29.6 g respectively, whereas the mean shell length and total weight after 380 days was 69 mm and 47 g, with 7.6 mm and 17.4 g annual mean increment.

Despite the close similarity in length growth between the two samples, the growth in weight derived from the tagged-recaptured abalone was remarkably different to that of tank tagged samples (Table 3.12).

Table 3.12 Growth increment in shell length and in total weight for *Haliotis mariae* tagged samples (released and recovered from the wild, and for the reared samples in tanks) after a period of one year (April 2004-April 2005).

Samples	Growth increments range		Average growth	
	Length (mm)	Weight (g)	Average growth in length (mm)	Average growth in weight (g)
Wild recovered samples	5.9 - 16.9	0.1 -21.5	8.7	5.2
Tank samples	0.2 – 14.1	6.4 - 29	7.6	17.4

The wild recovered samples showed negative increment in weight with most of the samples (19 samples), whereas the tank samples showed negative increment in weight in only one sample.

There was great variation in weight growth between wild recovered samples and tank group; the tank samples grew faster than those from the wild recovered. Observations on changes in maturation stage for tank tagged samples suggest that *Haliotis mariae* completed a reproductive cycle over a year.

3.3.10 Proximate biochemical composition

Proximate amounts (percentages) of Moisture, Protein, Fat, Ash, and Carbohydrate in foot muscle derived from male and female wild caught abalone from three stations: Mirbat, Hadbin, and Sharbithat are presented in Tables 3.13, 3.14 and 3.15 respectively.

Muscle tissue moisture, protein, fat, ash, and carbohydrate contents for the male from Mirbat station ranged from 61.8-75.85%, 14.19-20.22%, 2.28-3.04%, 1.46%-2.05%, and -0.14-19.2% respectively, whereas the female values ranged from 64-74%, 15.59-22.27%, 1.17-3.15%, 1.35-2.01%, and -0.23-15.11% respectively (Table 3.13). The percentages for the males at Hadbin station ranged from 62.6-78%, 13.53-21.25%, 2.28-3.21%, 1.47-2.19%, and -1.6-18.46% respectively, whereas the values for females ranged from 63.45-75.5%, 15.75-23.22%, 2.46-3.26%, 1.42-1.99%, and -0.27-16.16% respectively (Table 3.14). Sharbithat station values for the males ranged from 63.35-75.75%, 12.48-22.38%, 2-2.98%, 1.57-2.05%, and 1.18-16.69% respectively, whereas the female values ranged from 63.55-74.9%, 14.26-20.1%, 2.17-3.18%, 1.54-1.94%, and 1.57-15.77% respectively (Table 3.15).

Table 3.13 Monthly changes in proximate composition of the foot muscle of male and female abalone (*Haliotis mariae*), caught from Mirbat station during the period April 2003-March 2005.

	Male					Female				
Month	Moisture %	Protein %	Fat %	Ash %	Carbohydrate %	Moisture %	Protein %	Fat %	Ash %	Carbohydrate %
Apr-03	70.1	17.37	2.28	1.98	8.27	69.1	18.09	2.6	2.01	8.2
May-03	70.3	14.19	2.9	2.05	10.56	66.65	16.6	2.48	2	12.27
Jun-03	72.6	19.58	2.96	1.79	3.07	71.5	18.38	3.1	1.78	5.24
Jul-03	71.4	19.37	3.04	1.95	4.24					
Aug-03						69.8	18.45	2.8	1.75	7.2
Sep-03	71.05	18	2.88	1.79	6.28	69.4	19.1	2.82	1.66	7.02
Oct-03	67.2	16.58	3.04	1.46	11.72	65.25	17.89	2.67	1.51	12.68
Nov-03	61.8	18.06	2.98	1.48	15.68	65.2	15.59	3.1	1.46	14.65
Dec-03	69.1	18.45	2.76	1.55	8.14	66.75	18.49	2.45	1.71	10.6
Jan-04	67.9	16.89	2.62	1.57	11.02	69	17.82	3.15	1.61	8.42
Feb-04	66.6	18.41	2.6	1.6	10.79	66.6	18.41	2.6	1.6	10.79
Mar-04	70.95	18.61	2.98	1.7	5.76	68.1	19.81	2.81	1.69	7.59
Apr-04	70.75	18.22	2.9	1.62	6.51	73.9	22.21	2.76	1.5	-0.37
May-04	74.5	17.61	2.5	1.81	3.58	74	18.77	2.55	1.88	2.8
Jun-04	70.85	17.43	2.7	1.77	7.25	70.55	19.38	3.13	1.69	5.25
Jul-04	75.85	19.43	3.02	1.84	-0.14	73.05	22.67	2.77	1.74	-0.23
Aug-04	72.7	17.16	2.56	1.74	5.84	71.8	17.19	2.6	1.56	6.85
Sep-04	70.9	16.21	2.5	1.55	8.84	69.7	17.4	2.55	1.53	8.82
Oct-04	61.9	14.99	2.4	1.51	19.2	65.7	17.32	2.71	1.5	12.77
Nov-04	68.3	15.38	2.78	1.53	12.01	67.95	16.46	2.53	1.35	11.71
Dec-04	68.6	18.7	2.82	1.57	8.31	68.75	20.13	2.38	1.72	7.02
Jan-05	66.4	18.74	2.61	1.6	10.65	70.45	22.27	2.66	1.69	2.93
Feb-05	69.25	17.83	2.57	1.61	8.74	70.6	18.92	2.65	1.74	6.09
Mar-05	71.35	20.22	3.04	1.78	3.61	64	18.17	1.17	1.55	15.11

Table 3.14 Monthly changes in proximate composition of the foot muscle of male and female abalone (*Haliotis mariae*), caught from Hadbin station during the period April 2003-March 2005.

	Male					Female				
Month	Moisture %	Protein %	Fat %	Ash %	Carbohydrate %	Moisture %	Protein %	Fat %	Ash %	Carbohydrate %
Apr-03	70.2	20.69	2.88	1.82	4.41	69.45	23.22	2.51	1.84	2.98
May-03	68.4	19.37	2.68	1.73	7.82	65.6	19.54	2.57	1.72	10.57
Jun-03	72.3	21.25	2.95	1.81	1.69	69.8	20.59	2.79	1.72	5.1
Jul-03	70.5	18.12	2.83	1.69	6.86	69.1	18.75	2.9	1.68	7.57
Aug-03	72.1	18.12	3.09	1.79	4.9					
Sep-03	70.3	16.82	2.95	1.69	8.24	69.45	16.39	2.77	1.63	9.76
Oct-03	62.6	14.38	3.08	1.48	18.46	65.75	16.22	2.95	1.42	13.66
Nov-03	69.7	17.38	2.65	1.54	8.73	67.9	17.06	2.64	1.59	10.81
Dec-03	67.1	19.53	2.98	1.53	8.86	65	20.51	3.26	1.74	9.49
Jan-04	69.6	18.24	2.65	1.83	7.68	67.85	18.3	2.75	1.7	9.4
Feb-04	68.6	19.95	2.92	1.72	6.81	68.2	17.12	3.02	1.9	9.76
Mar-04	70.65	20.35	3.21	1.74	4.05	69.65	19.35	3.05	1.59	6.36
Apr-04	70.7	19.92	3.12	1.82	4.44	71	21.03	2.89	1.71	3.37
May-04	74.9	20.4	3.06	1.93	-0.29	72.4	21.26	3.04	1.88	1.42
Jun-04	73.7	19.92	3.1	1.8	1.48	73.9	19.45	3.05	1.92	1.68
Jul-04	78	18.47	2.94	2.19	-1.6	75.5	19.79	3.06	1.92	-0.27
Aug-04	71.5	17	2.69	1.75	7.06	73.4	17.31	2.57	1.99	4.73
Sep-04	70.95	13.53	2.56	1.62	11.34	67.3	15.75	2.46	1.63	12.86
Oct-04	66.5	17.56	2.9	1.47	11.57	63.45	16.51	2.35	1.53	16.16
Nov-04	68.3	16	2.28	1.65	11.77	67.6	16.28	2.64	1.59	11.89
Dec-04	63.1	19.16	2.46	1.53	13.75	68.4	21.13	2.61	1.69	6.17
Jan-05	69.65	18.02	2.42	1.64	8.27	65.85	17.27	2.44	1.63	12.81
Feb-05	68.8	20.55	2.72	1.81	6.12	69.5	18.72	2.69	1.67	7.42
Mar-05	69.8	18.79	3	1.52	6.89	64.3	20.73	2.36	1.67	10.94

Table 3.15 Monthly changes in proximate composition of the foot muscle of male and female abalone (*Haliotis mariae*), caught from Sharbithat station during the period April 2003-March 2005.

	Male					Female				
Month	Moisture %	Protein %	Fat %	Ash %	Carbohydrate %	Moisture %	Protein %	Fat %	Ash %	Carbohydrate %
Apr-03	67.9	15.66	2.23	1.69	12.52	72.2	17.83	2.34	1.75	5.88
May-03	69.3	18.74	2.39	1.91	7.66	70.4	19.98	2.78	1.83	5.01
Jun-03										
Jul-03										
Aug-03										
Sep-03	66.55	17.13	2.7	1.77	11.85	66.55	17.65	2.55	1.67	11.58
Oct-03	68.7	13.6	2.98	1.61	13.11	63.55	16.53	2.47	1.68	15.77
Nov-03	66.8	18.4	2.34	1.66	10.8					
Dec-03	69.15	18.56	2.65	1.57	8.07	68.15	17.8	2.72	1.71	9.62
Jan-04	65.3	17.92	2.75	1.82	12.21	69.75	17.51	2.8	1.94	8
Feb-04	64.7	15.06	2.4	1.82	16.02	66.8	17.04	2.59	1.63	11.94
Mar-04	67	15.41	2.77	1.64	13.18	72.35	17.01	2.83	1.84	5.97
Apr-04	73.8	16.68	2.49	2.05	4.98	73.2	18.81	2.87	1.72	3.4
May-04	75.75	18.29	2.78	2	1.18	73.3	20.1	3.18	1.85	1.57
Jun-04										
Jul-04										
Aug-04										
Sep-04	73.25	12.48	2.47	1.92	9.88	71.15	14.26	2.33	1.68	10.58
Oct-04	64.95	14.51	2.25	1.6	16.69	67.15	15.09	2.17	1.63	13.96
Nov-04	63.35	14.53	2	1.69	18.43	68.7	17.63	2.26	1.54	9.87
Dec-04	68.95	16.71	2.21	1.72	10.41	69.9	19.1	2.32	1.67	7.01
Jan-05	67.35	22.38	2.3	1.95	6.02	70.45	19.48	2.42	1.86	5.79
Feb-05	67.65	16	2.5	1.83	12.02	68.55	15.38	2.56	1.81	11.7
Mar-05	75.05	16.91	2.2	2.01	3.83	74.9	18.85	2.62	1.64	1.99

The average amount of moisture varied significantly. The males showed higher levels of moisture between June and August in the first year with a peak during June (72.45%), and between April and September with a peak in July (76.93%) during the second year. These two peaks were followed by a decrease towards the lower levels which were observed between September 2003 and March 2004, with the lowest levels during October and November 2003 at 66.17% and 66.10% respectively during the first year, and between October 2004 and February 2005 with the lowest level during October 2004 at 64.45% during the second year. The females were found to follow a similar trend of moisture contents to the males and the highest level 74.28% was observed during July 2004, while the lowest level 64.85% was during October 2003 (Figure 3.16).

Protein in males was present in high amounts during June, July, August, and December in the first year, and between March and July and between December and March in the second year, with the highest level, 20.42%, during June 2003.

Except for December 2003, the lowest amounts were observed between September 2003 and February 2004, and between August and November 2004, with the lowest levels during October 2003 and September 2004 being 14.85% and 14.07% respectively. The females showed the same trend as the males and the highest level, 21.23%, was during July 2004, while the lowest levels were during November 2003 and October 2004, with 16.33% and 16.31% respectively (Figure 3.16).

Fat content was found to vary: The male fat content increased significantly from April to August 2003, showing the highest level during August at 3.09%, followed by a decrease and fluctuation towards February 2004. The lowest levels in the first year were observed during April, March, November 2003, and February 2004, being 2.46%, 2.66%, 2.66%, and 2.64% respectively. From March 2004 to July 2004 the fat content increased and fluctuated, and high levels were observed during March, June, and July, at 2.99%, 2.90%, and 2.98% respectively. This increase was followed by a decrease toward November 2004 showing the lowest level of fat content at 2.35%. A similar trend of fat content was observed with the females, and the highest levels were observed during June and July 2003, and June and July 2004, at 2.95%, 2.90%, and 3.09%, 2.92% respectively. The lowest values were observed during September and October 2004, and March 2005 at 2.45%, 2.41%, and 2.05% respectively (Figure 3.16).

Ash contents of males were highest between April and August 2003 and April and July 2004 with the highest levels during May and July 2004 being 2.02% and 1.91% respectively, whereas the lowest were observed between September 2003 and March 2004, August 2004 and March 2005, with the lowest content during October 2003 and October 2004 at 1.52% and 1.53% respectively. Similarly, the amount of ash for the females was high between April and August 2003, and between May and August 2004, with the highest content during April 2003 and May 2004 being 1.87% and 1.87% respectively. Except in January 2004, the lowest contents were observed between September 2003 and April 2004 in the first year, and between September 2004 and March 2005 in the second year, with the lowest levels recorded during October and November 2003, and October and November 2004 being 1.54%, 1.53%, 1.55%, and 1.49% respectively (Figure 3.16).

In contrast to all the above compositions, which showed higher levels during or around June and July, and lower levels during or around October and November, the carbohydrate content showed an opposite trend. The carbohydrate content varied significantly. Except in April and May 2003, it showed higher levels between

September 2003 and February 2004 in the first year, with highest level observed during October 2003 being 14.43%, and between September 2004 and February 2005 in the second year with the highest level during October 2004 being 15.82%. Lower levels were observed between June and August 2003 in the first year, and between March and August 2004 in the second year (Figure 3.16).

The females followed the same trend as males, with higher carbohydrate levels between September and February 2003 in the first year, and between September and November 2004 in the second year, with the highest levels during October 2003 and October 2004 being 14.0% and 14.30% respectively, whereas lower values, except in May 2003, were observed between April and August 2003 in the first year, and between March and August 2004 in the second year, with the lowest levels at June 2003 and July 2004 being 2.38% and -0.87% respectively.

Among the proximate composition, moisture, ash, and carbohydrate were higher in the male than the female, whereas protein and fat were higher in the female than the male (Figure 3.16).

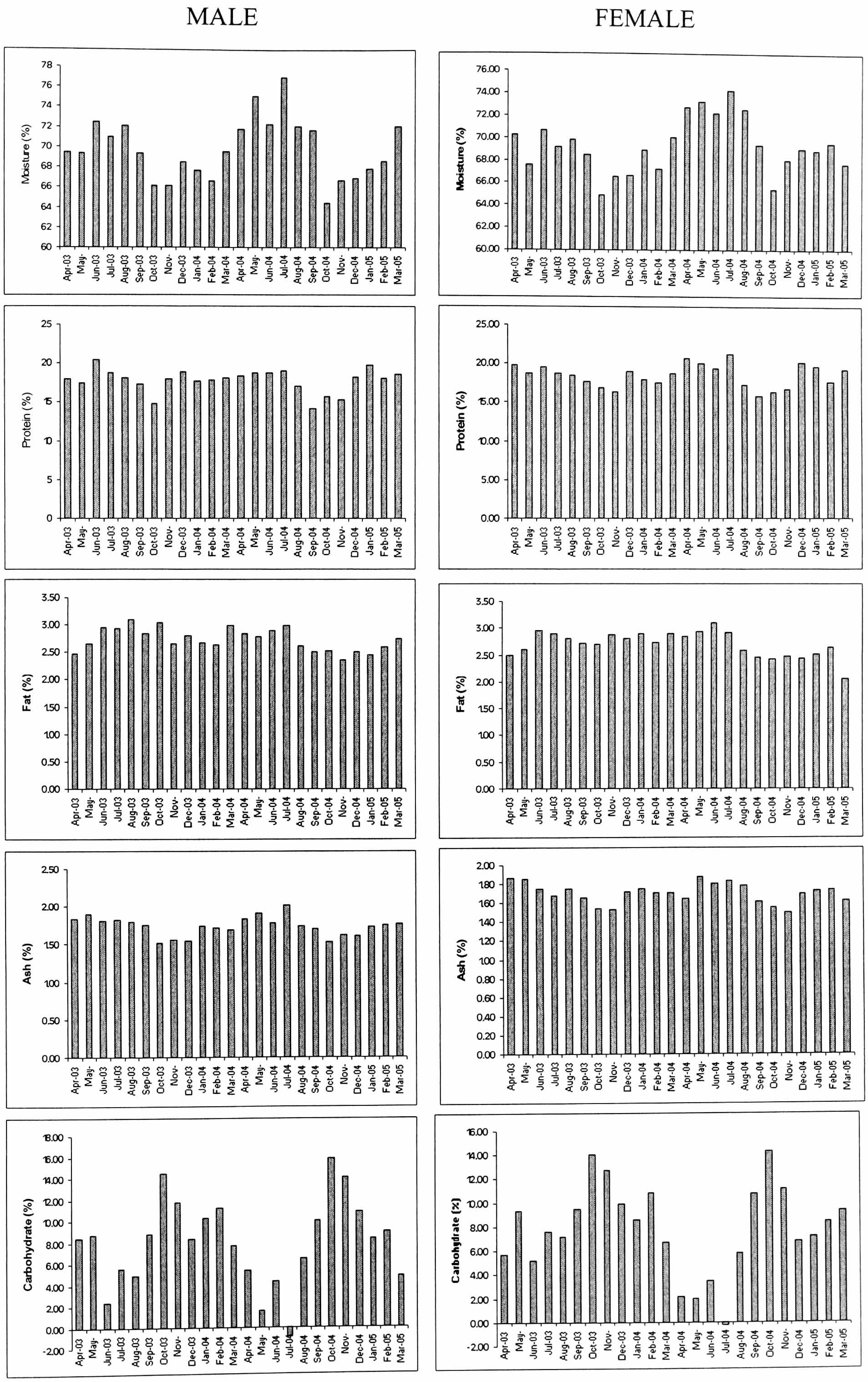


Figure 3.16 Mean monthly variation in proximate biochemical composition (moisture, protein, fat, ash and carbohydrate) in foot muscle of male and female abalone (*Haliotis mariae*) during the period April 2003-March 2005.

3.3.11 Abalone preservation (Drying process and weight losses)

Most of Oman's abalone production is exported in dried form to the South East Asian market, mainly Hong Kong. The processing of this product takes place during the fishing season and is carried out by the traders themselves. The average weight of fresh foot muscle samples used in this study for the illegal size groups (< 90 mm SL) before processing was 30.8g with an average shell length of 83.9 mm, whereas the average weight of legal size groups (> 90 mm SL) was 66.2g with an average shell length of 104.1 mm.

The results of the study show high loss in the final average weight of the dried product; about 64.7% of the initial weight. Table 3.16 illustrates the weight losses among different size groups (< 90 mm & > 90 mm) during the drying period. The weight losses during the preservation steps (drying period) were higher during the first day and decreased gradually with time. The average weight losses during the whole drying period for illegal and legal size groups were approximately 65.2% and 64.2% respectively.

Table 3.16 The remains average and percentage weight of abalone samples during drying process (preservation experiment) for illegal sizes (< 90mm SL), and legal sizes (> 90 mm SL), and the overall remains weight and percentage for combined groups.

	< 90 mm group		> 90 mm group		Average for two groups	
Drying time (days)	Weight (g)	% of remain weight	Weight (g)	% of remain weight	Weight (g)	% of remain weight
0	30.8	100	66.2	100	48.5	100
1	19.7	63.8	54.2	67.6	32.4	65.7
3	13.8	44.7	33.4	49.6	23.6	47.1
7	11.5	37.1	27.5	40.7	19.5	38.9
18	10.7	34.8	23.9	35.8	17.3	35.3

These results are nearly in accordance with the previous finding of the moisture content in the abalone foot muscle, recorded in this study at 69% (See section Biochemical Composition).

The final remains weight for the dried illegal size groups was 34.8% of the initial weight of the raw abalone, whereas for the legal size groups it was 35.8% of the initial weight (Table 3.16). The time required for optimum required drying is suggested to be 7-10 days (Figure 3.17). The products in this stage turned to a golden colour and were translucent when exposed to the suns rays or to a light source, which are indicators of good drying and are important requirements in the Asian market.

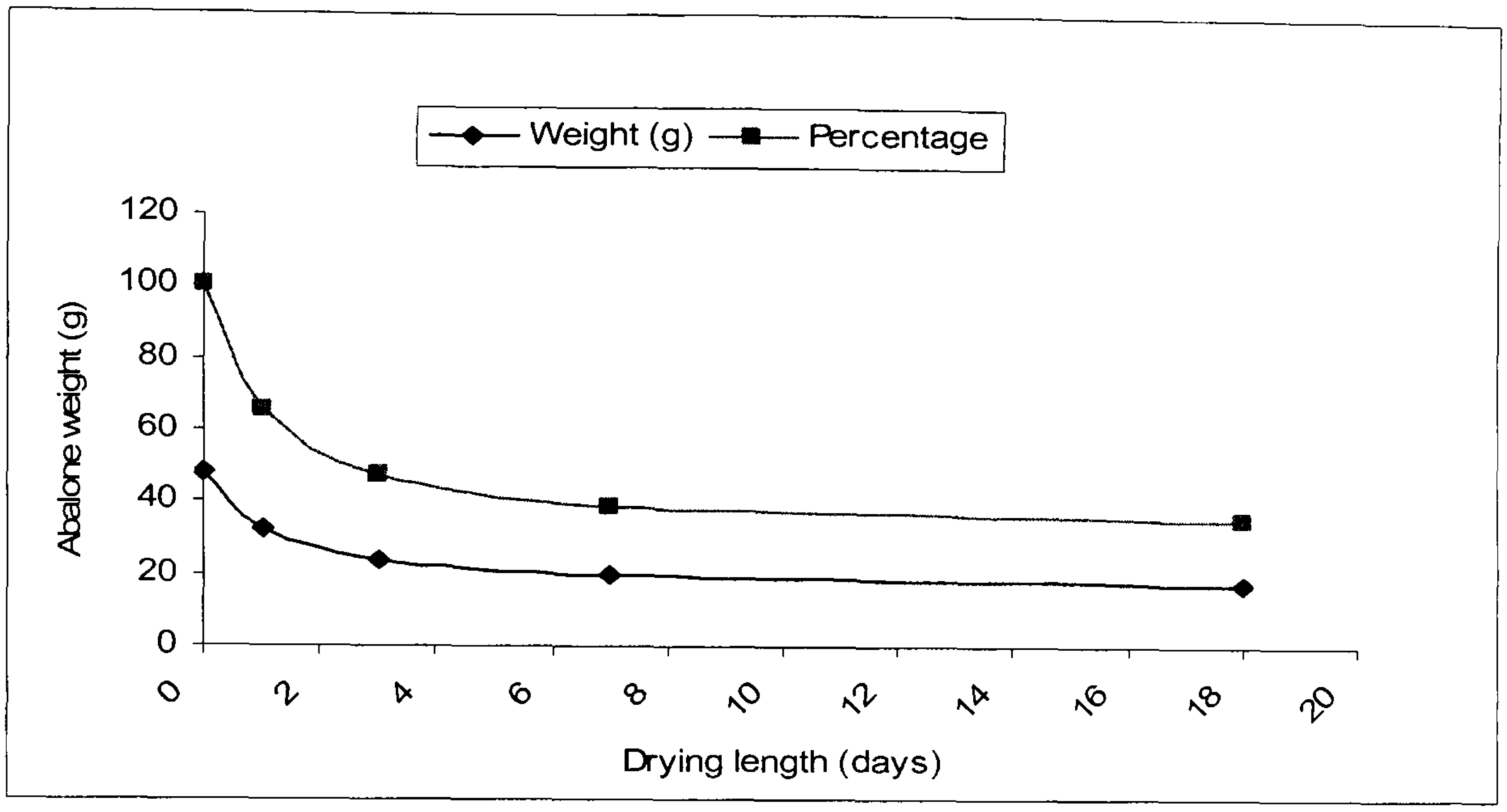


Figure 3.17 Decrease in weight (g) of abalone foot muscle during the preservation process (drying length, days) for a period of 18 days. Loss in weight is higher during the first week, after which it stabilizes.

3.4 Discussion

3.4.1 Environmental conditions

Determining the seasonal changes in environmental conditions prevailing off the southern coast of Oman is necessary to understand the ecological characteristics of the abalone populations and the fishery characteristics.

According to Wyrtki (1973) and Vidal-Junemann (1981) the southern coastline of Oman is influenced by strong and persistent southwest monsoon winds from April through October, with maximum effect in July and August. These replace the northeast winds which prevail in the northern winter, resulting in a major reversal of the current system in the northern Indian Ocean. Full reversal of the current pattern is achieved from November through to April (Luther *et al.*, 1985).

Major changes in the environmental conditions are created by this wind in both the intertidal and subtidal zones; these occur largely as a result of the upwelling of deep cold nutrient-rich water, when water temperatures decrease from around 25 °C between October and May to 17 °C between June and September.

The upwelling areas are generally known as the most biologically productive areas and this is reflected in the potential yields of fish, lobster and abalone in these regions, derived from the injection of nutrients into the euphotic zone by the upwelling of the deeper, cooler water. Ryther *et al.* (1966), Qasim (1977), and Smith (1984) described this phenomenon in the northwestern Indian Ocean. The latter mentioned that the productivity of the upwelling area of this region is equal in magnitude to the productivity of the Peruvian upwelling area.

Although the upwelling waters are a feature of the entire coastline, small areas of local intensity occur between Mirbat and Sharbithat, which have particularly interesting floral and faunal communities. Barrett *et al.* (1984) revealed the presence of a unique macroalgal flora in the littoral and sub-littoral zones of the rocky segments of the southern Oman coast.

The characteristic of the upwelling and its distribution may be modified in the littoral and sublittoral zones by local factors. Examples of such local factors include: small-scale circulation patterns as dictated by coastal morphology; bathymetric variations; locally increased biological activity in the shore zone; and increased wave activity (Savidge *et al.*, 1986)

The drop in water temperatures at the shore waters between June and September, associated with the presence of oxygen poor water, could also be due to fresh water input flooded to the sea during the monsoon season. This brings organic materials to the sea and the processes of decomposition using oxygen could be a possible cause of environmental stress. This is possibly reflected in the seasonal mass mortality of sardines and other marine life in the inshore waters along the southern coastline of Oman during May and June each year. Such stressful conditions could affect the growth of abalone.

3.4.2 Samples during the fishing season (Divers' landing samples)

The abalone fishery is restricted to the southern region of Oman, and according to the fishing law, fishing zones are identified among the country regions, thus, only local citizens of the southern region are allowed to harvest abalone. However, many people from other regions ignore the law and flock southward during the abalone fishing season to be involved in the diving activities and earn better money than they would from other fisheries in their regions. Unfortunately, the rapid and huge annual increase in numbers of either non-local divers or new divers from the internal parts of the same region, have led to a major increase in take and heavy fishing rate. As a consequence the fishery has declined markedly, and landing data since 1988 provide strong evidence that the stock is dangerously overexploited. In 1988, the landing was around 50 t, but declined to 29 t in 1999 (Dep. of Fisheries Statistics, 2003). This is despite a reduction in the fishing season from six to two months since 1991 combined with the introduction of minimum legal size limit of 90 mm. Under the present situation, the sizes recorded reflect the significant decline in the fishery stock, especially in Mirbat and Hadbin, where more than 50% of the divers' catch was below the minimum legal size. This is because the biology of abalone and its occurrence in shallow waters makes it particularly vulnerable to over exploitation. Currently, illegal harvesting is a problem with most abalone fisheries throughout the world. Despite a myriad of laws and penalties in many countries, the illegal catch has continued to increase, approaching 40% of the total world legal fisheries in 2002 (Gordon & Cook 2001, 2004). This has led to the depletion and serious decline or even to the collapse of many fisheries worldwide, such as in British Colombia and United States. Moreover, some fisheries have been closed, such as in South Africa. Once the fishery is depleted, abalone stocks do not generally recover quickly.

In Oman over the last 16 years, the commercial catch of abalone has fluctuated and declined from about 50 to 29 t/yr (Dep. of Fisheries Statistics, 2003). By far, the most important and major reasons for this decline are the illegal harvesting by either fishing out of the permitted season and/or collecting the small immature abalone were the illegal landings exceed 50% of the catch, loss of habitat and environmental destruction through turning over the rocks and boulders by divers. Despite the fishing law in place, the rules are not strictly enforced and the penalties are not strongly applied. The minimum harvestable size, which was placed on *Haliotis mariae* in order to protect the small immature abalone, was ignored by most of the divers, and turning over the boulders when searching for abalone has become a normal practice among many divers.

Johnson & Shepherd (1992) reported, for a sample taken at the beginning of 1991 fishing season at some sites of Oman, that 50% of the catch was undersize, and at the end of the season, this ratio was 90% at some areas.
These results are not surprising considering the low densities of abalone at all the three sites at 0.07 individuals/m^2 (see Chapter 4), and where the remaining abalone stocks are mostly of small sizes, more so at Mirbat and Hadbin than at Sharbithat, which is most likely due to the lower pressure on the fishery at Sharbithat. The illegal catch recorded at Sharbithat was only 26.3% of the divers' landings compared with 57.7% and 50.5% at the other two areas respectively. This is due to the accessibility of these areas, which are served by asphalted access roads, and to the lack of large sized abalone, causing a tendency for the increased number of divers at these two sites to collect any abalone they can see.

The demand for abalone is continuous and the high price of *Haliotis mariae* which has increased from 21 O.R. per kilogram of fresh flesh to 70 O.R. (54-181 US$) is a strong incentive for divers and shore pickers to take every abalone they can find, leaving nothing for the future. However, many local divers are obliged to dive and sell their catch to specific traders under personal loan agreements established between the abalone traders and fishermen during the rest of the year; repayment of loans forces divers to maximize their productivity, so, their effort is higher than expected.

The size structure of landing during the fishing season suggests that fishing intensity is so high that abalone less than a year old and still immature are taken, and very few sexually mature abalone are left. This affects recruitment and depletes spawning stock. In addition, as a substantial proportion of small sizes below the minimum legal size (< 90 mm) are found in inshore shallow waters, they are easy targets for shore pickers (women, elderly and beginner divers), who cannot dive in deep water. This poses a major threat to recruitment and a real risk of stock collapse in locations where illegal fishing is prevalent.

The ineffective enforcement of law, combined with the weak and inadequate fines and penalties, encourage many local divers to ignore the regulations to protect the resource, and dive out of season, particularly in the weeks before the season starts.

This is basically to be ahead of the rest, in order to catch the bigger abalone before other divers from other regions come and collect them at the beginning of the season. These divers usually gain access to the fishing ground through sheltered gullies in remote areas, and in places away from the inspectors' reach, where access to the resource can be from the shore or by boat. The divers also operate at night, as well as during the day. The lucrative market among local abalone traders also encourages divers to work, and most of the illegal harvest finds its way to the commercial market with the season's exported produce. The abalone traders maximise their financial rewards from these illegal activities. The traders usually pay the divers half of the in-season price, about 20-25 O.R./kg of fresh flesh (52-65 US$). Accordingly, the responsible authorities should make it more difficult for illegal divers or traders by tightening up accountability and audit requirements for export. The existence of out-of-season activity is corroborated by high landing statistics on the first day of the season at some sites, because divers working before the season are gathering abalone and hiding them in lobster traps or in semi-closed crevices that are well-known to them, to be harvested and landed at the beginning of the season. In this study, the current fishing season was found to coincide the spawning season for this species. Ogawa (1997) similarly reported that most *Haliotis mariae* were fully mature and ready to spawn during the fishing season, and, as a result of permit diving during this period, and the effect of diving out off season, the number of mature abalone decreased dramatically, affecting the rate of reproduction.

3.4.3 Morphometry

Morphometric analysis was carried out to quantify variability between the three sites, as well as between males and females. There were significant difference, for all the morphometric parameters (shell length, shell width, total weight, flesh weight and shell weight) between the different sites ($P<0.05$). All were higher at Sharbithat. This may be due to the lower pressure on the fishery in this area, where abalone is still relatively in large. Hadbin showed lower values, and Mirbat low still. These two areas are close to the divers' homes, and so they have been heavily fished during the last few years. Males and females showed differences in shell length, shell width and flesh weight. Females' values were always higher compared with males.

Changes in morphometry among sites are particularly relevant to environmental conditions and food availability associated with the monsoon season. The biometric relations are useful for converting catch landings to live weight or checking legal minimum sizes of shelled abalone. The morphometric analyses conducted here therefore provide a useful baseline for reference in future studies.

3.4.4 Size composition of samples (monthly length frequency)

The size composition of the samples varied slightly among sites and with time. The range of most samples collected during the whole study period from Hadbin and Mirbat extended below the minimum legal size (MLS) of 90 mm SL, and only a few exceeded 120 mm. However, more large sized individuals were caught at Sharbithat.

This variation in size composition among the three sites was most likely due to the lack of large size specimens, which seems to be linked to the greater fishing pressures during the last few years, especially at Hadbin and Mirbat compared with Sharbithat. This has led to a decline in the population and the exploitation of large sizes of *Haliotis mariae*.

The mean size at first capture for Omani abalone *Haliotis mariae* was assumed by Sanders (1982) to be 85 mm SL. He found a mean SL of 96 mm for exploited stocks (< 8m depth) and 105 mm for unexploited (> 8m depth). Johnson *et al.* (1992) suggested a mean size at first capture for the same fishery at about 65 mm SL, with a mean SL of 97 mm.

The results of the present study suggested mean sizes for the remaining stocks at 82.3 mm, 83.3 and 97.4 mm for Mirbat, Hadbin and Sharbithat respectively, with overall mean size for the fishery at 87.6 mm. This mean size is below the minimum legal size and is just around the size at first capture reported above by Sanders, which could be considered a direct indicator of the serious depletion of this fishery.

3.4.5 Sex ratio

The sex ratio of the monthly sampled abalone throughout the study period deviated slightly from the expected ratio of 1:1, indicating distribution of more adult males than females in the population. This conflicts with the findings on other abalone species, such as *H. midae, H. carcherodii, H. rufescens, H. tuberculata* where males and females are recorded in equal numbers, or in some populations, females slightly outnumber males (Crofts, 1937; Boolootain *et al.*, 1962; Newman, 1967; Bussarawit *et al.*, 1990).

Sanders (1982) reported the sex ratio of Omani abalone *Haliotis mariae* to be 1:1, whereas Shepherd *et al.* (1995) suggested more males for the same fishery. The results of the present study suggested the opposite trend for *Haliotis mariae*. This may have arisen because the females are larger compared with available males and fishing pressure on them was greater, thus depleting the number of females in the fishing ground. A similar trend was recorded for the seasonal variation in sex ratio distribution at all the three sites. The presence of females in the samples was low between April and September, whereas larger numbers of males were recorded. Between October and April, both sexes were present in similar proportions at Mirbat and Hadbin, whereas Sharbithat showed slightly more males. The equality in sex ratio during this period may be due to the aggregation for spawning during this period, which was found to be the reproductive season.

3.4.6 Gonad Index and spawning season

The Haliotidae are dioecious broadcast spawners (Webber, 1977). In haliotids, the gonad surrounds the digestive gland and the two organs together are referred to as the conical appendage (Boolootain *et al.*, 1962; Newman, 1967; Young & DeMartini, 1970; Poore, 1973). The sexes are separate and distinguished by the colour of the gonad, being generally creamy white in males and dark green in females. Sections cut through the conical appendage are used to calculate a gonad index (Boolootain *et al.*, 1962), and the change in this index through time has often been used to describe the annual reproductive cycle of haliotids (e.g. Shepherd & Laws, 1974; Sainsbury, 1982).

In *Haliotis,* the period of gonad growth coincides with that of an abundant food supply (Shepherd & Law, 1974) and optimal feeding possibilities (Shepherd, 1973). In the southern coast of Oman this occurs after the monsoon season.

Tanaka *et al.* (1986) showed that seasonal variations in temperature act as an important factor that controls the breeding cycle and the reproductive biology of several species of *Haliotis,* and they usually spawn after sudden temperature falls.

Based on the systematic observations that were made throughout the year, and on the basis of the results of the gonad index analysis in this study, *Haliotis mariae* breed once per year, associated with the decrease in water temperature between November and March). The spawning is restricted to the same time at all the three sites, and it occurs from November to March or maybe April. Spawning was found to occur at similar times by Sanders (1982), Savidge *et al.* (1986) and Siddeek *et al.* (1993), but Shepherd *et al.* (1995) found the reproductive season extended from January until the end of March, and Ogawa (1997) indicated that the spawning season in Sadah Bay was from January, or maybe December, until March.

The fishing season of *Haliotis mariae* in Oman is from 15 October to 15 December, which is immediately prior to the spawning season. To encourage recruitment it is suggested the fishing season should be moved after the spawning season, perhaps from April to May, and reduced to only one month, to conserve the endangered and overexploited fishery.

3.4.7 Maturity stages

Morphological observation of colour, shape and size of the gonads in relation to the level of the shell periphery was carried out for a period of two years to determine the maturity stages. Occurrence of maturity stages observed were analysed and their percentage was calculated month-wise. Maturity of *Haliotis mariae* showed four stages (an immature stage followed by three mature stages) and the cyclic reproductive behaviour was completed over one year. Both sexes showed a similar trend, but varied between locations. The early stages (stage one and two) dominate the population between May and October at Mirbat and between March and October at Hadbin, whereas at Sharbithat they are between April and October. The advanced stage (stage three) was dominant between November and April at Mirbat and between November and February at Hadbin, whereas at Sharbithat it was between November and March. Spawning season was determined based on distribution of the different maturity stages, particularly the dominance of advanced stages with respect to time. On the basis of the occurrence and dominance of the advanced maturity stages, the months from November to April inclusive appear to be the months of spawning at all the three sites. Thus, *Haliotis mariae* spawns once a year during these months. This is corroborated by the gonad index study, together with the results of previous studies (Sanders, 1982; Savidge *et al.*, 1986; Siddeek *et al.*, 1993; Shepherd *et al.*, 1995; Ogawa, 1997).

3.4.8 Size at first maturity

Few studies have mentioned the size of sexual maturity for *Haliotis mariae* of Oman, giving a range of results from 65 mm SL to 76 mm shell length (SL). Shepherd *et al.* (1995), reported that sexual maturity at Hadbin occurred between 60 mm and 100 mm SL, and 50% are sexually mature at about 75 mm SL, whereas at Sharbithat 100% of the population were sexually mature at 75 mm SL. The age at first spawning has been suggested to be at the third year (2+ cohort) (Sanders, 1982). Shepherd *et al.,* (1995) and Johnson *et al.*, (1992) indicated that the size of sexual maturity for *Haliotis mariae* was < 76 mm SL. They indicated that the percentage of abalone less than 70 mm SL landed increased from 2.1% in 1984 to 3.2% in 1985 to 7.2% in 1987-8. The mean size and proportion of small abalone in divers' catch also vary over time and between localities.

Sizes at first maturity obtained in this study varied among the three sites, but it followed the same trend for both male and female. Mirbat and Hadbin samples showed maturity at 60 mm SL, whereas at Sharbithat it was at 70 mm. This means that significant numbers of immature abalone are landed each year during the fishing season and out of the season by rule breakers. However, there are very few large sized individuals remaining. The abalone fishery is therefore under threat and may collapse unless immediate and real action is taken by the responsible bodies to monitor landings. The 90 mm SL minimum legal size needs to be enforced strongly to safeguard and protect this important resource, and to ensure that enough stock are left to reproduce.

3.4.9 Growth estimation & Mortality of *Haliotis mariae*

Growth of abalone is affected by several interrelated environmental factors. It is greatly influenced by the type and level of food available as well as a range of environmental conditions, which affect the physiological functions of the organism. Some of these factors include feed rate and duration, water temperature, and competitors' density. Moreover, generally, the growth of this species is often seasonal, and the abalone usually grow well when optimum water temperature and food are available. They normally grow at 20-30 mm a year; it takes 4 years to grow to the marketable size of more than 90 mm. In some cases, however, their growth is very slow; only 10 mm a year, so that it takes longer to reach the commercial size.

The growth in some abalone species might be faster, as much as 30-50mm SL a year under good feeding conditions and suitable environmental factors. Abalone tend to grow very slowly when sea temperature is low and during the spawning season (Day & Fleming, 1992).

This study is of longer duration than any previous study on *Haliotis mariae* of Oman, and enabled growth in length and weight to be observed for one year. Most of the released tagged abalone failed to grow in weight and cope with the expected normal growth rate and show negative weight increments while on the other hand, tank tagged samples showed a better growth rate.
The unexpected growth in weight obtained for the released tagged abalone may be due to the scarcity of food sources in the released site, which later (during the recovery stage) has been observed, with heavy degradation in algal cover compared with other abalone grounds. Whereas, enough supplementary food was available to the reared abalone all year around. The low growth in length for both samples might also be due to the stress resulted from handling and tagging.

The poor recovery rate of wild-tagged samples (15%) was largely due to the changes that occurred in the abalone habitat at the release site during severe rough sea associated with the monsoon, which was observed during the recovery stage. This might be also the reason behind the negative growth in weight of most of the samples (19 samples out of 30 recovered samples). The range of shell length of the released tagged samples was between 46.8-71 mm, whereas the range of the reared samples was between 40.3-74.8 mm. These sizes may have been too large and unsuitable for the growth experiment. Also, most of the recovered abalone shells were infested with the boring sponge *Cliona* and the boring polychaete *Polydora*. Infestation was low in younger samples but increased exponentially in larger samples. This, also, might be behind the negative results obtained in this study, as the growth of this species was reported to be faster in the first year and decrease with age (Shepherd *et al.*, 1995).

The growth of this species in Omani waters has been reported by different authors in previous different studies. Shepherd *et al.*, (1995) reported growth of this species measured by analysis of modal progressions of cohorts in length-frequency data, mark-recapture data and frequency of primary growth checks. The annual increase in shell length was about 43 mm in the first year and 20-25 mm in the second and third years. They suggest that annual increment declines with age, and seasonal growth rates varied between age classes. They assume an average growth rate of 23 mm / year. Stirn & Al-Hashmi (1996) reported that growth rate of Omani *Haliotis mariae* is higher than in other abalone species, i.e. greater than 36 mm SL increment per year.

Whilst the growth rate of *Haliotis mariae* reported by previous studies appears to be sound, this has not been confirmed across the entire geographic range. Therefore, as growth might vary among the different fishing grounds depending on food availability and environmental conditions, it remains important to conduct further studies to cover the growth range of this species throughout its distribution range. Reported growth rate together with the results of this study all indicated that *Haliotis mariae* takes not less than 3-4 years to reach the commercial size of 90 mm SL. Thus, the divers' claim that abalone could reach the commercial size in a few months is incorrect.

The observed tagged abalone in the tanks during the period of the study (one year) showed changes in the gonad development cycle. The recorded gonad stages of most individuals developed with time and completed the gonad development cycle within the year. The animals spawned once, which indicates their yearly spawning season. Therefore, it is evidente that *Haliotis mariae* reproduce on a yearly basis.

Mortality

Several authors have studied mortality of *Haliotis mariae* in the Omani waters: Sanders (1982) estimated fishing mortality (*F*) at 0.1 and natural mortality (*M*) at 0.6. Siddeek & Johnson (1993) obtained the mortality values for this fishery during the 1987-88 to 1989-90 and during 1991 at Sadah and Hadbin sites. Total mortality (*Z*) was similar at the two sites during the 1987-88 to 1989-90 seasons at 1.7 $year^{-1}$ for male and 1.57 $year^{-1}$ for female. This has been suggested as a sign of overexploitation (where *F/Z* was suggested to be at least 0.68). The *Z* value in 1991 was estimated at the beginning of the fishing season (November) 1991 at 2.37 $year^{-1}$ at Sadah for combined sexes, whereas it was 1.66 $year^{-1}$ at Hadbin at the end of the season (December) for combined sexes, which indicates different total mortality at each site. The (*Z*) values estimated in 1991 were higher than those of 1987-88 and 1988-89, indicating increase in fishing pressure. The researchers suggested that divers reached declining returns on the Sadah ground and abandoned harvest efforts before the season ended, after fishing out almost all the large sizes; harvesting continued in the Hadbin ground until the end of the season with increased fishing pressure. Fishing mortality at Hadbin has also been suggested to be much higher in December than in November.

The natural mortality (*M)* for this fishery is not well known. Shepherd *et al.* (1995) indicated that the values of natural mortality (*M*) for *Haliotis mariae* estimated by Sanders (1982) are unreliable. They concluded that the highest reliable estimates for natural mortality *(M)* for adults reported in the published values of *(M*) for abalone species reviewed by Shepherd & Breen (1992) are around 0.5 for species emergent in the adult phase in cryptic species; thus, they suggested *(M)* for this fishery to be in the range of 0.2-0.4.
They also noted that *Haliotis mariae* of Oman is found in cryptic habitat throughout life, where the sea temperature is in the range 18-28 °C, a transitional warm-temperature to subtropical region. Taking into account this factor, they considered the range of natural mortality (*M*) for this species to be between 0.3-0.5, and the fishing mortality (*F*) in the range 0.6-1.2, whereas the value of total mortality (*Z*) was suggested to be 0.99-1.59, depending on the site.

Egg- per-recruit analysis for this fishery reported by Shepherd *et al.*, (1995) indicated that at the present age at first capture, egg production level is 2-29% of the unfished stock, which is considered far too low to maintain recruitment. Depending on their experience and information gained from other abalone fisheries about egg production levels, they suggested egg production levels for this fishery at 40% as a minimum acceptable level to maintain the fishery. At this egg production level, the appropriate age at first capture was suggested to be 4 to 5 years, which would require a size limit of between 109-115 mm SL.

Siddeek & Johnson (1993) depending on egg-per-recruit, mature biomass-per-recruit and yield-per-recruit analyses (they did not present data) indicated increased fishing pressure on this fishery, and suggested a reduction of 50% in the fishing mortality level at Sadah combined with increase in the minimum size limit to at least 110 mm SL to conserve the remaining stock.

The unusual very early sexual maturity of *Haliotis mariae* which has been reported to spawn at the first year (Stirn & Al-Hashmi, 1996) is supported by the fast and high growth rate of this species at the first year (Shepherd *et al.*, 1995; Stirn & Al-Hashmi, 1996). This might partially explain why the abalone fishery in Oman has been less overexploited during the last years and still not collapsed, as one would expect, looking at the heavy harvesting.

The present high fishing mortality, low stock density (0.07 individuals/m^2) (see Chapter 4), unavailability of large sizes, decline in catch rate, and the very low egg production level, are evidence of recruitment overfishing and are indicators of the imminent collapse of this fishery if no urgent action is taken to protect this resource.

3.4.10 Proximate biochemical composition

No previous studies have been made on the biochemical composition of *Haliotis mariae* of Oman. In this study special care was taken that the samples were adults in the same size range. The results of this study showed high variability in proximate biochemical composition profiles of abalone foot muscle throughout the year. However, there were no consedirable differences in proximate composition among the three sites, and the changes in the muscle contents followed the same trend for both sexes. The contents of moisture, ash, and carbohydrate were a little higher in males than females, whereas protein and fat showed the opposite trend. Although the changes of fat content in muscle tissues were similar to those of ash, they were much lower than those of moisture, carbohydrate, and protein at all the three sites, for both sexes. Moisture, protein, fat, and ash contents reached their highest levels during and around June and July in both sexes, and thereafter decreased toward October and November, whereas carbohydrate showed the opposite trend. The small observed differences in proximate composition among the three sites might be partially explained by differences in food availability, which varied among them. This also might be behind the small differences between the male and female contents.

On the one hand, this is probably due to the fact that high levels of biochemical composition are associated with the availability of food sources (Nelson *et al.*, 2002a). Macroalgae are considered the main abalone nutrition source, and their availability vary seasonally and geographically (Nelson *et al.*, 2002b). The availability and abundance of these macroalgae communities at the southern coast of Oman are restricted by the monsoon season which occurs between June and September each year. Due to the upwelling associated with this season, the water temperature drops dramatically to reach its lowest level during August at 17 °C. Thereafter, the sea temperature starts to increase gradually to reach the highest level in November at 30 °C under the influence of the prevailing air temperature. The lower water temperature associated with the appearance of high levels of nutrient caused by this upwelling promotes the growth of kelp and other alga communities, but this only lasts for a short period before the water temperature rises again, resulting in the death and disappearance of these algae at this coast, and thus the loss of main food sources, which might have an effect on the growth and reproduction of abalone. Previous studies have demonstrated that food availability and temperature influence protein levels in the abalone foot muscle (Plant, 2002, Grubert & Ritar, 2003).

In this study protein was by far the major component and the higher levels between June and August reflect the availability of food sources during that period. Protein levels declined toward November. Thus muscle contents of proximate composition were significantly affected by temperature and food availability.
Although the decline of abalone population in Oman has been ascribed to overfishing which has been considered the main cause (Johnson & Shepherd, 1992; Johnson *et al.*, 1992; Al-Hafidh, 1999), it can be suggested that the impacts of environmental changes and lack of food sources during the rest of the year, due to their seasonality and to the rise in water temperature, have also contributed to this decline.
Ponce-Diaz *et al.* (2004) state that the combined effect of high temperature and optimum food must be discussed together because better growth and successful reproduction is associated with higher levels of protein, carbohydrate, and glycogen in muscle.

On the other hand, Mercer *et al.* (1993) state that the foot muscle and hepatic digestive gland serve as a storage depot for metabolic resources that are essential in the metabolism process, and which have an impact on growth and spawning. Studies on other molluscs indicated that the metabolism of energy resources may differ between species (Litaay & Silva. 2003). Although most elements of biochemical composition are important for the metabolism process, including carbohydrate and protein components, fat contents may be especially vital in this process (Nelson *et al.,* 2002a). Barber & Blake (1991) report that, during gametogenesis, digestive gland lipid is first metabolized, followed by muscle glycogen and finally protein reserves. Carefoot *et al.* (1998) reported that the digestive gland is involved in the transfer of assimilated food to body tissues in abalone, and its greatest relative size and metabolic activity would be expected to occur concomitantly with active gametogenesis.

Gonad development is considered to be an energy demanding process, as the mobilization of nutrients to the gonads occurs during gamete development (Litaay & Silva, 2003). Gabbott (1983) stated that lipid reserves are used in gametogenesis and lost during spawning, and that the lipid content fluctuation coincides with the reproductive cycle A study of Pacific oyster showed a higher percentage of lipid in ripe gonads and that lipid content decreased with spawning (Pazos *et al.*, 1997). These lipids are a major source of energy for embryogenesis and used for the formation of membranes in moslluscs (Soudant *et al.*, 1999).

Nelson *et al.* (2002) determined the lipid content in foot muscle tissue and in eggs of abalone *Haliotis laevigata* over a period of one year. The result showed variation between them. The total lipid of foot muscle decreased towards spawning, and was, however, much lower than the total lipid in eggs, which increased towards spawning. Utilization of biochemical stores is dependent on the physiological status of the animal and environmental conditions (Martnez *et al.*, 2000). Nelson *et al.* (2002a) reported that temperature induced changes in fatty acids which may be considered as important factors in gonodogenesis. Storage metabolism in *Haliotis mariae,* as in other molluscan species, is closely associated with reproductive events and represents an important biochemical pathway. Proximate analysis of *Haliotis mariae* foot muscles gave an indication of the changes of energy resources during the reproductive cycle. This means that the foot muscle storage of essential biochemicals probably supports abalone gonad development toward spawning, which results in the decrease of their levels.

For *Haliotis mariae*, we found that the gonads enter a period of growth beginning in September, attaining maximum size toward the end of November, perhaps December, which has been considered spawning season in this study. Thereafter growth declines towards the monsoon season in June. This continues until the end of September, at which time the gonads enter a quiescent period. Changes of proximate composition in *Haliotis mariae* foot muscle are in agreement with previous findings on gonadal development in *Haliotis mariae,* as well as in other molluscs.

The results of this study demonstrate variable variation in the proximate biochemical composition of abalone foot muscle during the year. They also provide initial evidence that biochemical composition of foot muscle is influenced by the availability of food sources and temperature, which has an impact on the spawning season. In addition, the combined results of biochemical composition and gonad development for *Haliotis mariae* suggest that the spawning season occurs between November and February. Thus, in order to conserve the remaining threatened stock, the current fishing season must be changed. It seems that shifting the fishing season to be between March and June would be suitable and beneficial to the fishery.
For *Haliotis maria*, however, there are still no direct studies on the specific function of these compositions. Further investigations are needed to elucidate detailed pathways for different functions, and to increase our understanding of the ecologic values of these influences.

3.4.11 Abalone preservation (Drying process and weight losses)

Abalone in some countries are marketed in different forms (live, fresh, frozen, canned, dried), each of which is priced differently. The price is also influenced by abalone size, processing method, packaging and economic conditions (Gordon & Cook, 2001, 2004). In Oman the dried abalone has been considered the main export form for several years. This probably began before refrigeration, and continues today as demand for dried abalone from the Asian market has increased rapidly. In these countries dried abalone is usually used in traditional recipes and more commonly prepared for special or ceremonial occasions. There are various processing methods used to create dried abalone. Some of these methods are very special and expensive, and the process takes a long time to complete. These processing methods usually use coals and ceramic cooking utensils with slow cooking for the preparation of dried abalone. However, the price for the final product is very high; "a minimum of US$ 700 per kilo and as much as $ 12,000 per kilo or more" (Gordon & Cook 2001). The Omani dried abalone preparation is done in a very simple way, which consists of boiling the abalone in sea water and sun drying until they become dried enough. Using this method results, as this study has shown, in significant loss in weight of the final product; the average percentage of weight loss was about 64.7% of the initial weight of the raw abalone during the drying period, and the conserved weight was only 35.3% of the initial weight. For example, 1 kilogram of fresh abalone foot muscle, after being cooked and sun dried for the required drying time of 10 days, will yield only an average of 353g of dried abalone. The weight loss also varies among the size groups; the illegal sizes groups (<90mm) lost more weight during the drying process, about 65.2% of their initial weight, yielding only 34.8%, whereas the legal size group lost less weight (64.2%) and then yielded more weight, 35.8% of their initial weight. This is perhaps due to the soft tissues of the small sizes, which contain more moisture. Thus, by accepting these small illegal sizes, the abalone traders reduce their financial returns and so reduce the overall benefits from the fishery as a whole. The average ratio of wet weight to dried weight that could be used in the conversion of any of the two forms to the other is (1 wet weight = 0.353 dry weight) Even though the difference between the yields of two groups is very small, on a large scale and in view of the high price of this product, it makes a difference, particularly when considering that most of the abalone production in Oman is of small sizes. For example, while the total abalone landing during 2004 was 57 tons of fresh abalone meat, about 50% of this amount was below the minimum legal size. Converting the illegal quantity (28.5t) to dry weight would yield 9918 kg of dried abalone (28500kg wet weight × 0.348g dry weight), while if this quantity was within the legal size limit, then it would yield 10203 kg (28500kg × 0.358g). The loss in weight in this case is about 285 kg of dried product, which is valued at US$ 199500 (285 kg × 700 US$). This amount has been estimated on the basis of minimum market price, and it might be higher if the market prices were higher. Even though the traders are still making profit by buying and processing abalone, when the weight loss of these small sizes is taken into account, the selling prices of these illegal products tend to revert back to the purchasing prices. This loss could be reduced, to the benefit of different user groups as well as the fishery which could be maintained, if the fishery was well controlled and proper care was given to the resource.

CHAPTER 4

SURVEY ON *Haliotis mariae* POPULATION AND STOCK ESTIMATION

4.1 Introduction

Sufailah or the Omani abalone *Haliotis mariae* is found over a small coastal area between Mirbat and Sharbithat at the southern region of Oman. This fishery is managed on a basis of regulating the size of animals captured (> 90 mm shell length), restricting the fishing season to two months from 15 October to 15 December, a minimum diving depth of 8 m, and a ban on using any artificial breathing gears (Ministry of Agriculture and Fisheries, 1994). Effective management always requires wide knowledge of the resource aspects, but in Oman the state of *Haliotis mariae* fishery is uncertain, as it is in some abalone fisheries around the world. This arises from lack of studies on this species. There have been limited studies on abalone resources in Oman. The first survey was performed by Mardella International, Ltd. in 1975 during an investigation on the marine shellfish resources of the country, when they discovered the abalone fishery in the southern region of Oman (Waleed Associates, 1981). The second attempt was an investigation of the potential for commercial shellfish operation in the southern region (Dhofar region) of the Sultanate of Oman carried out by Waleed Associates (1981). The third and the last investigation, before the present study, was a preliminary field survey of the abalone resources which was carried out by FAO in 1982 in the south east coast of Oman (Sanders, 1982). Since then there has been no field survey on the status of this fishery in Oman.

In many abalone fisheries, stock assessment has seldom been successful, primarily because of the difficulty in accurately estimating abundance (Breen, 1992). The monitoring of these fisheries often relies heavily on traditional indirect indices of stock abundance such as catch per unit of effort (CPUE) to provide indications of trends in stock abundance (Tegner, 1989).

The CPUE trends for the Omani abalone fishery of *Haliotis mariae* up to 1998 indicated a continuous gradual decline and fluctuations in landings (Al-Hafidh, 1999). Moreover, there were frequent complaints from the abalone divers and merchants that abalone was becoming scarce, and most of the landings during the last few years were of small sizes (Divers Pers.Com 2003).

As a response to such problems, it became essential to attempt a direct survey of *Haliotis mariae* stock.

The survey of abalone stocks over large spatial scale provides estimates of relative abundance, and important information about different aspects of the fishery (McShane, 1994). The objectives of the *Haliotis mariae* survey were to identify the distribution and estimate current stock abundance of this fishery along the coastline and at different depths, to assess the stock structure and size classes, to identify abalone habitat associations, competitors, predators, and to estimate the algal cover and food availability. Moreover, it also aimed to determine the environmental conditions influence the resource, and whether the stock showed signs of overexploitation. It was expected that, if the fishery is over fished, the population would reflect a very low density and a very limited range of size classes above the minimum legal size (MLS) of 90 mm shell length. In addition, sub-legal abalone (< 90 mm) would also be expected to be in low densities.

4.2 Materials and Methods

The present survey covers all the abalone grounds between Mirbat and Sharbithat along the southern coastline of Oman. The survey was conducted from 23 March to 25 April 2005, at the five major commercial sites: Mirbat, Sadah, Hadbin, Hasik, and Sharbithat in thirty sites spaced between Ras Mirbat and Ras Qerwaw (Suqrah) (Figure 4.1). These are the main fishing grounds and have a variety of different habitats (see Chapter 3)

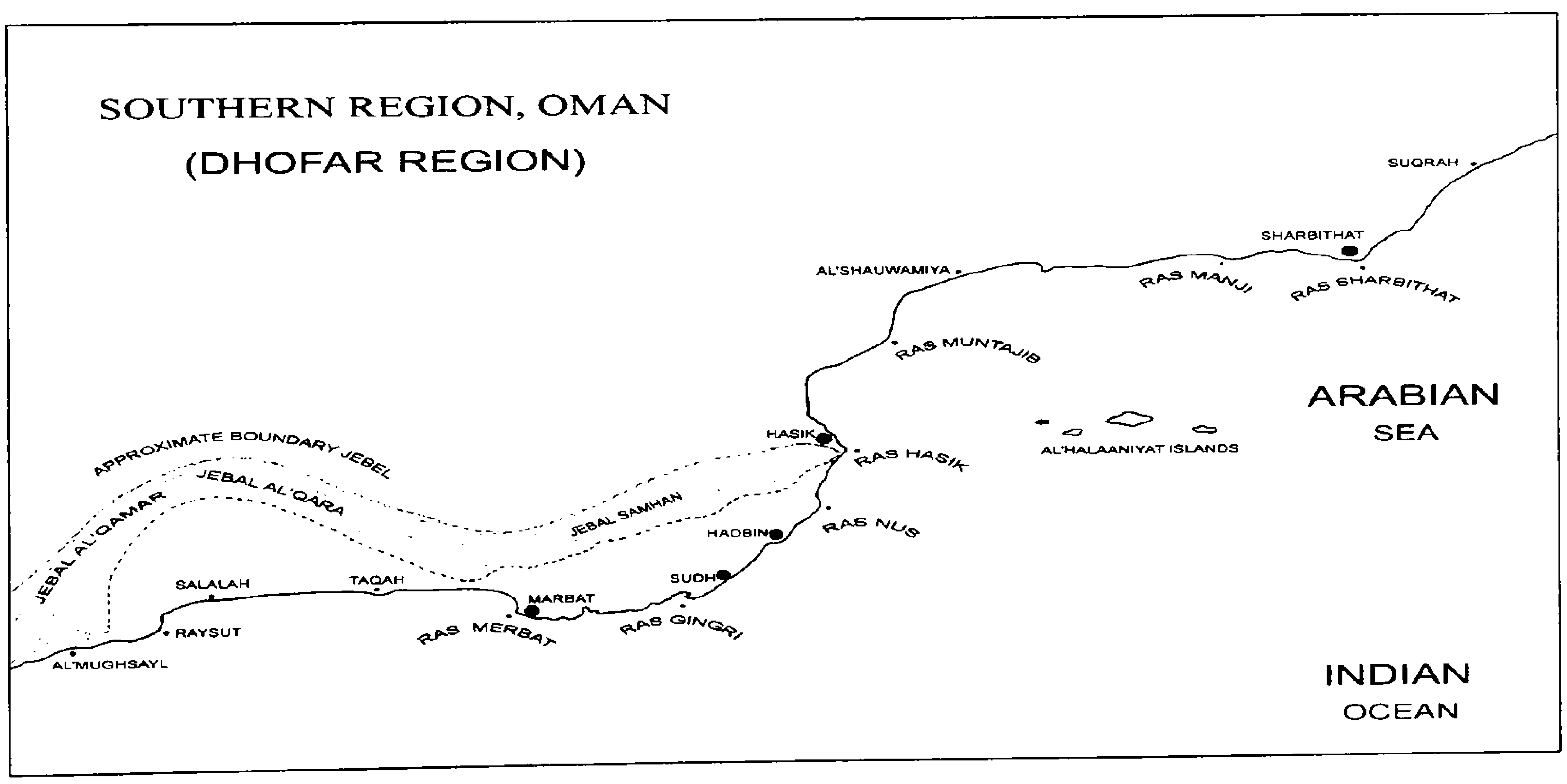


Figure 4.1 The coastline of the Southern region of Oman and the five surveyed areas (Mirbat, Sadah, Hadbin, Hasik and Sharbithat) between Ras Mirbat and Suqrah.

A SCUBA dive survey of the abalone beds was carried out by a team of divers, including the researcher, from Raysut Fisheries Research Laboratory, supported by three local professional abalone divers. The team was under the supervision of the researcher. The survey consisted of a total of sixty dives, and large areas of seabed were involved in this survey. Generally, abalone populations tend to be patchy in their distribution on a scale of several metres or even a hundred metres (Schiel, 1992; Guzman del Proo, 1992; Shepherd & Johnson, 1991). It was, therefore, advisable to cover as large an area of seabed as possible during any dive, to obtain as representative as possible coverage of the seabed (Peck & Culley, 1990).
The selected sites at each of the five areas were sampled twice using two methods: the transect survey method described in Cripps & Campell (1998), which appeared more practical to use in estimating the distribution and abundance at gradually increasing depth, because abalone densities are known to differ with depth; and the classical quadrate method (Shepherd & Johnson 1991). The same procedure was used with both methods, and deep and shallow populations of abalone were sampled.

The surveys were conducted from a 25ft fibreglass boat with 2×40 ph outboard engines. The sites were selected after discussion with commercial divers and prior visits to the fishing grounds. During the survey, if a site did not have suitable habitat for *Haliotis mariae* (i.e. sandy bottom or no reef habitat or if the depth was > 20 metres) another site was selected. Surveys were limited to 20 m depth, because *Haliotis mariae* has a preference for shallow habitat < 20 m. Once a site was selected, a weighted transect line 160 m long, flagged each 10 m, was randomly placed perpendicular to the shore. The weighted transect line was placed along the bottom by two divers, who fixed it by two small anchors at each end, marked with two visible floaters. The transects were placed from deep water until the water depth became too shallow with consideration to the effect of sea conditions (e.g. surge or waves) to allow divers to continue.

The survey procedure involved two research divers, one on each side, starting from the deep point toward the shore searching for and collecting all emergent and cryptic abalone seen on the top of and under rocks, in cracks and crevices within 1 metre on each side of the line. Each diver used his own arm span, equivalent to 1 metre, to determine the width of the swathe, occasionally checking with the line for confirmation. All abalone samples found within the transect, regardless of size, were collected in pre-numbered net bags for each 10-metre length of the transect line. Simultaneously, another diver was engaged in recording the depth at each 10m point along the transect line, counting and recording the number of sea urchin, associated animals (competitors and predators), algal cover, habitat information, and any observation within the specific study area.

Counts and depths were recorded every 10 metres along the transect, resulting in 32 counts, each covering 10 m^2 of seabed. This method provided information regarding the distribution, abundance, and patchiness of abalone and associated animals; it also provided details about the abalone habitat and algal communities. A similar procedure was used with the 10×10 m quadrate transect, which represented a surveyed area of 100 m^2.

All the abalone samples collected during the course of this survey were taken to the camping site where they were measured and shell length of every abalone was measured by Vernier calipers to the nearest millimetre. The sex of each sample was recorded; those with cream coloured gonads were males, and those with green coloured gonads were females.

On the assumption that the size composition of the samples counted along the transect was representative of those of the stock, the estimated size frequency distribution and abundance of the actual population in each 320 m^2 transect was calculated. The counts, being recorded every 10 m^2, gave an indication of the population distribution over the seabed within the recorded depth, and the sum of the divers' counts provided data on the density of abalone over a 320 m^2 sector of seabed.

The primary objective of the diving survey was one of standing stock assessment and quantitative records were made of other biota encountered on the transect. Also comments were recorded about significant features observed during the survey. The kelp communities along the study areas within which the abalone occurred were recorded.

The survey was extremely manpower-intensive and time consuming, which imposed certain constraints on which surveys could be carried out at areas which were thought to be old abalone grounds, such as around Masirah Island and Al'Halaniyat Island.

The numbers of surveyed transects in each of the five areas was 6 transect lines, and 6 quadrate transects, except at Sharbithat where only 4 transect lines and 4 quadrate transects were surveyed, due to bad weather and rough sea, and at Hadbine, where 8 transect lines and 8 quadrates were surveyed due to its importance as a main landing site (Table 4.1).

Table 4.1 Location of the surveyed sites within the five major abalone landing areas along the southern coastline of Oman.

Study Areas	**Latitude**	**Longitude**
Mirbat Sites:		
Power house bay	16° ,57.923 N	054° ,42.383 E
Hino Island	16° ,58.050 N	054° ,41.649 E
Ras Al'Hanani	16° ,58.073 N	054° ,41.949 E
Ras A'tyar	16° ,57.330 N	054° ,50.380 E
Aadeen bay	16° ,57.598 N	054° ,51.978 E
Gingiri bay	17° ,00.151 N	055° ,01.406 E
Sadah Sites:		
Ras Hout	17° ,02.154 N	055° ,04.069 E
Al'khoor bay	17° ,03.564 N	055° ,05.435 E
Hatt bay	17° ,04.212 N	055° ,06.302 E
Al'maahalah bay	17° ,04.842 N	055° ,06.775 E
As'sala Wa Al'raha bay	17° ,06.788 N	055° ,08.150 E
Foshi bay	17° ,07.290 N	055° ,09.626 E
Hadbin Sites:		
Wkallaaat bay	17° ,08.418 N	055° ,11.587 E
Har (Dharh Ash'shoom)	17° ,09.177 N	055° ,11.726 E
Aryal bay (Communication tower bay)	17° ,11.072 N	055° ,12.461 E
Hadbin school bay	17° ,11.483 N	055° ,13.275 E
Hadbin harbour bay	17° ,12.046 N	055° ,14.071 E
Hasellt bay	17° ,12.384 N	055° ,14.261 E
Oloyi bay	17° ,13.331 N	055° ,15.132 E
Ras Noos	17° ,14.262 N	055° ,15.569 E
Hasik Sites:		
Noos bay	17° ,17.435 N	055° ,15.503 E
Heettoom bay	17° ,19.439 N	055° ,16.526 E
Mahafa bay	17° ,22.050 N	005° ,17.399 E
Souq Hasik bay	17° ,22.051 N	055° ,18.052 E
Hasik harbour bay	17° ,25.164 N	055° ,17.212 E
Ras Hasik	17° ,23.569 N	055° ,18.069 E
Sharbithat Sites:		
Maghbeer	17° ,55.711 N	056° ,21.363 E
Al'Doohaaat	17° ,55.586 N	056° ,21.432 E
Shoabaaatt	17° ,55.350 N	056° ,21.293 E
Shoabaaatt	17° ,58.792 N	056° ,23.282 E

4.3 Results

4.3.1 Geographical Distribution

In the course of this survey, the geographical range of *Haliotis mariae* was restricted to the exposed typical rocky shores dominated by the availability of algae cover (during the monsoon) along the coastline between Ras Mirbat and Hasik, and in some rocky shores around Sharbithat and Suqrah. These results confirm and extend those of Waleed Associates (1981) and Sanders (1981) who recorded the distribution of this species between Mirbat and Hasik, and those of Johnson & Shepherd (1992) who noted *Haliotis mariae* between Mirbat and Sharbithat. Most of the exposed rocky shores along this coastline, with the exception of some small sandy coasts as well as the whole shores of Ash'Shuwaimyah, supported abalone bearing reef, but some of these shores supported few abalone, such as in Mirbat, Sharbithat and Hasik. During the last few years many divers have ignored these areas because of their low productivity, and concentrated closer to the abalone merchant camps at Hadbin to dive in shores with the greatest number of abalone adjacent to Sadah and Hadbin. No abalone were found east to Ras Hasik or along the coastline throughout Ash'Shuwaimyah. The short remarkable and complex rocky coast adjacent to Sharbithat showed some signs of abalone availability at Maghbeer, Shoabaat, and Mangi. Also, the *Haliotis mariae* range was found to be extended to the east, and was distributed in small areas around Suqrah (Figure 4.1 previous section)

Johnson & Shepherd (1992) reported the southern range of *Haliotis mariae* as extending to Masairah Island and Al'Halaniyat Island, but it has collapsed in these areas, and today there is no sign of any fishery operation.

The vertical distribution of this species was in both intertidal and subtidal zones, but it varied among the five areas. Small numbers of abalone were found in the intertidal zone, but the population occurs mainly between low water mark and a maximum depth of 20 metres. Although, most of the populations are of small and medium sizes, variation in the vertical distribution of different sized abalone was observed. Small abalone, i.e. those with mean shell length below 65 mm, occur most commonly under small boulders or in narrow crevices in shallow waters with depths below 5 metres. The intermediate sizes, with shell length of 65-75 mm, occur most often in the cracks and crevices in the reef and under big rocks, and are found in much deeper water between 5-10 m. The larger, commercially exploited sizes (> 90 mm SL) were recorded in small numbers, but they have a wider vertical distribution, and are found from the low water mark down to a depth of 20 m (Figure 4.2)

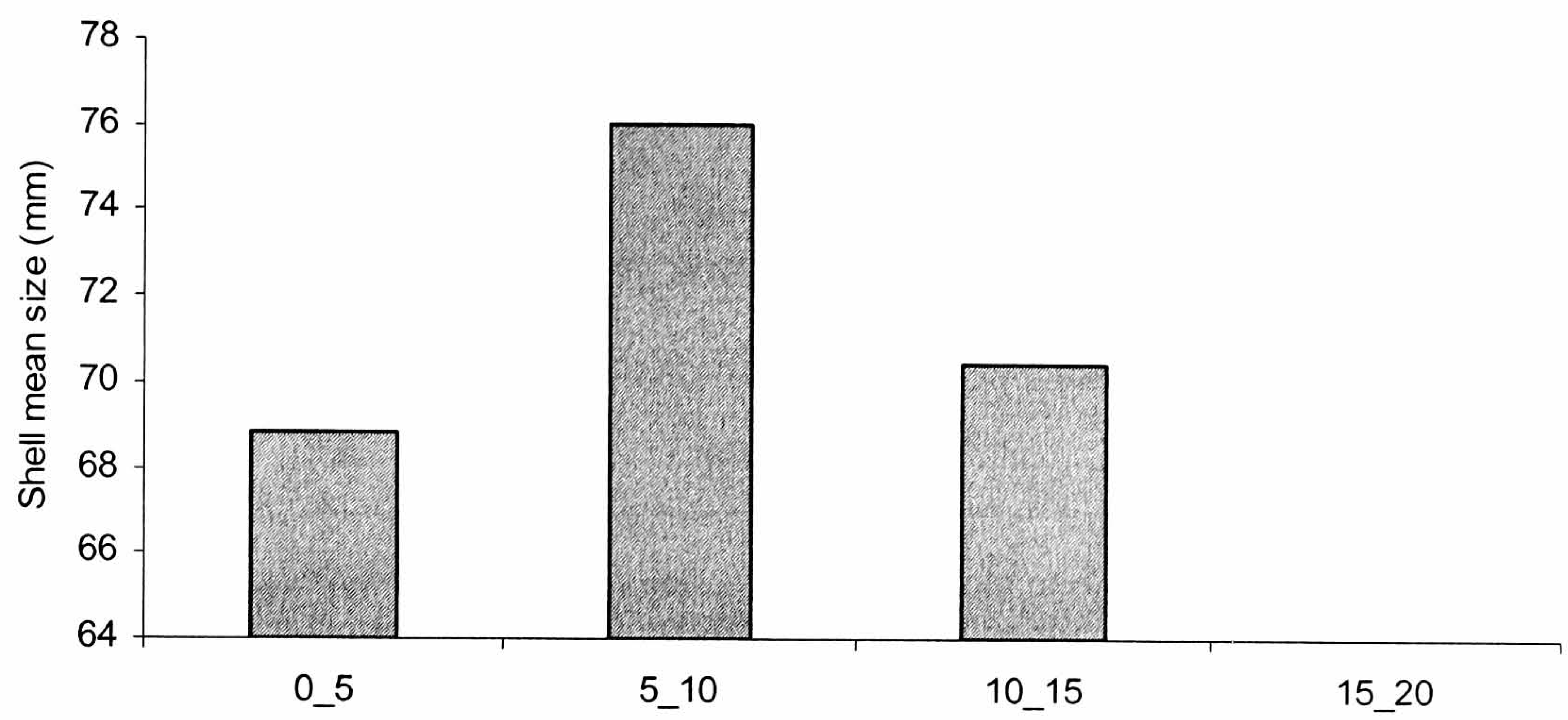


Figure 4.2 Distribution of abalone mean size with depth (m) at all fishing grounds

Abalone is known to aggregate rather than being uniformly distributed along the bottom and, when undisturbed by fishing, these aggregations or "beds" may be extremely dense and extensive (Shepherd & Johnson, 1991). Unfortunately, this natural and healthy phenomenon was not observed with *Haliotis mariae* populations at any site during the course of the survey. Commercial divers reported that in past years they removed between 30-40 pieces from such beds, but today they search a greater distance to find separated individuals. These indicators show the low density of the abalone population and the serious situation of the stock (Figure 4.3)

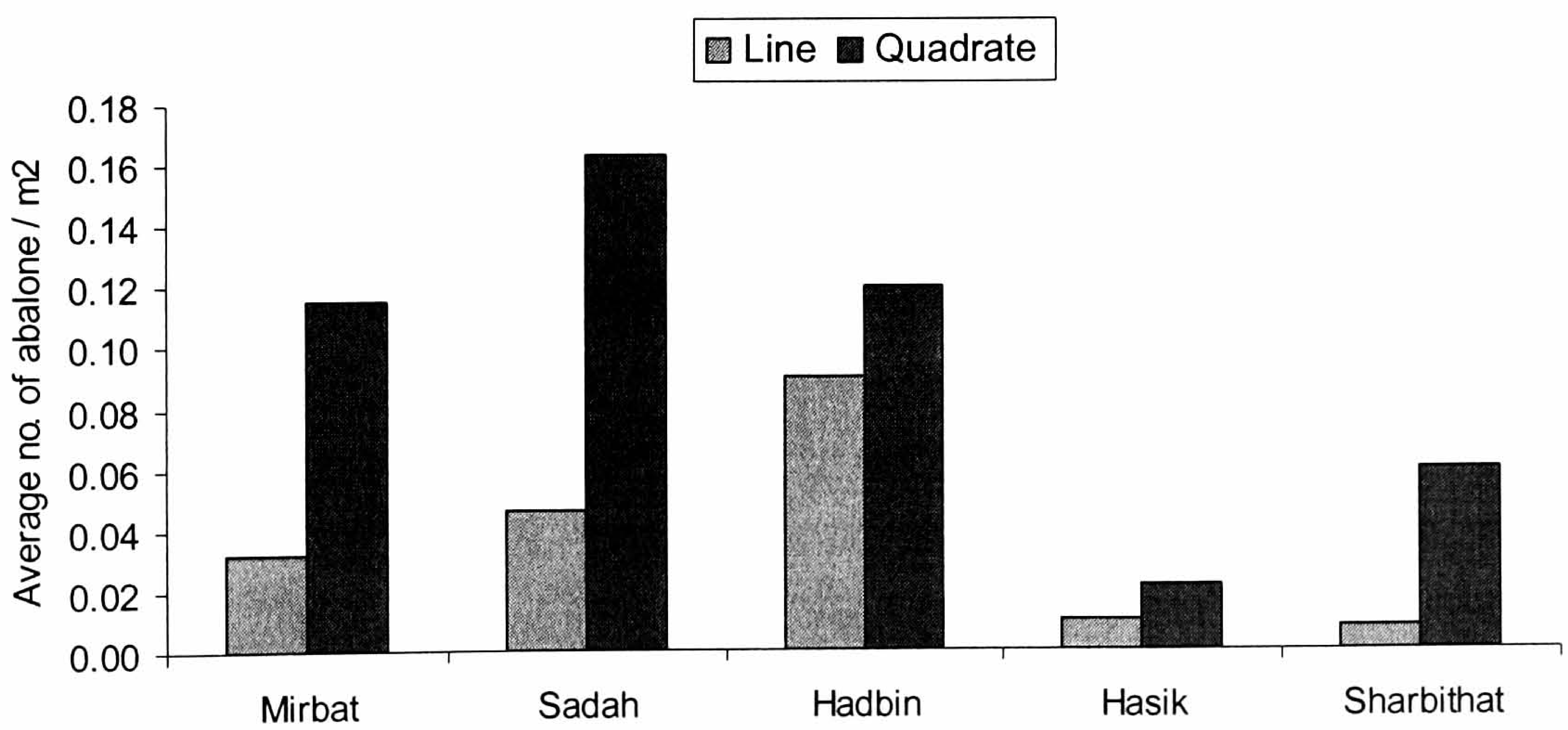


Figure 4.3 Abalone density obtained by transect line and quadrate at the five study areas.

Although the abalone is distributed along the coastline, commercial exploitation occurs mainly between Sadah and Hadbin. Diving takes place to a much lesser extent between Mirbat and Sadah, whereas east of Hasik and east of Sharbithat few divers are operating and few abalone are landed commercially. Around Suqrah there is a very limited area and only few divers operate there.

4.3.2 Abundance and Stock estimation

The total area covered during the survey at all the thirty sites within the five areas was 12,600 m². Within the thirty sites two methods were used at each site; the line transect which covered an area of 320 m², and the quadrate with an area of 100 m². The total number of abalone found within the total covered area was 710 individuals ranging in shell length between 20.6 mm and 121.8 mm; 410 individuals were found within the transect line, and 300 individuals at the quadrate, with an average of 11.9 individuals per transect line and 10 individuals per quadrate. The mean number per transect at the five study areas were found to be significantly different among them (Table 4.2)

Table 4.2 Average number of abalone per transect line (320 m²) and per quadrate (100 m²), and mean individuals/m² at transect and at quadrate, and the mean density/m² for combined methods at all sites.

	Mean no. / transect		Mean no./m²		
Studey areas	T. Line	T. Quadrate	T. Line	T. Quadrate	Density / m2
Mirbat	10.17	11.50	0.03	0.12	0.07
Sadah	14.83	16.33	0.05	0.16	0.10
Hadbin	28.87	12.00	0.09	0.12	0.11
Hasik	3.17	2.17	0.01	0.02	0.02
Sharbithat	2.50	6.00	0.01	0.06	0.03
Mean	11.91	9.60	0.04	0.10	0.07

During the survey, *Haliotis mariae* was seldom observed in aggregations of three individuals or more. Rarely emergent abalone were observed, mostly as single individuals in the crevices and cracks under the rocks or between the holdfast of the few remaining kelp and other large brown macroalgae.

Despite differences in the area size covered by the transect line and the quadrate, the average number of counted individuals per each method was similar at each site except for Hadbin, and Sharbithat. At the former, the average line transect counted double the number of individuals counted at the quadrate. By contrast, at Sharbithat the quadrate counted about twice the numbers of the transect line. This was due to variation in seabed topography and depths at these areas (Figure 4.4)

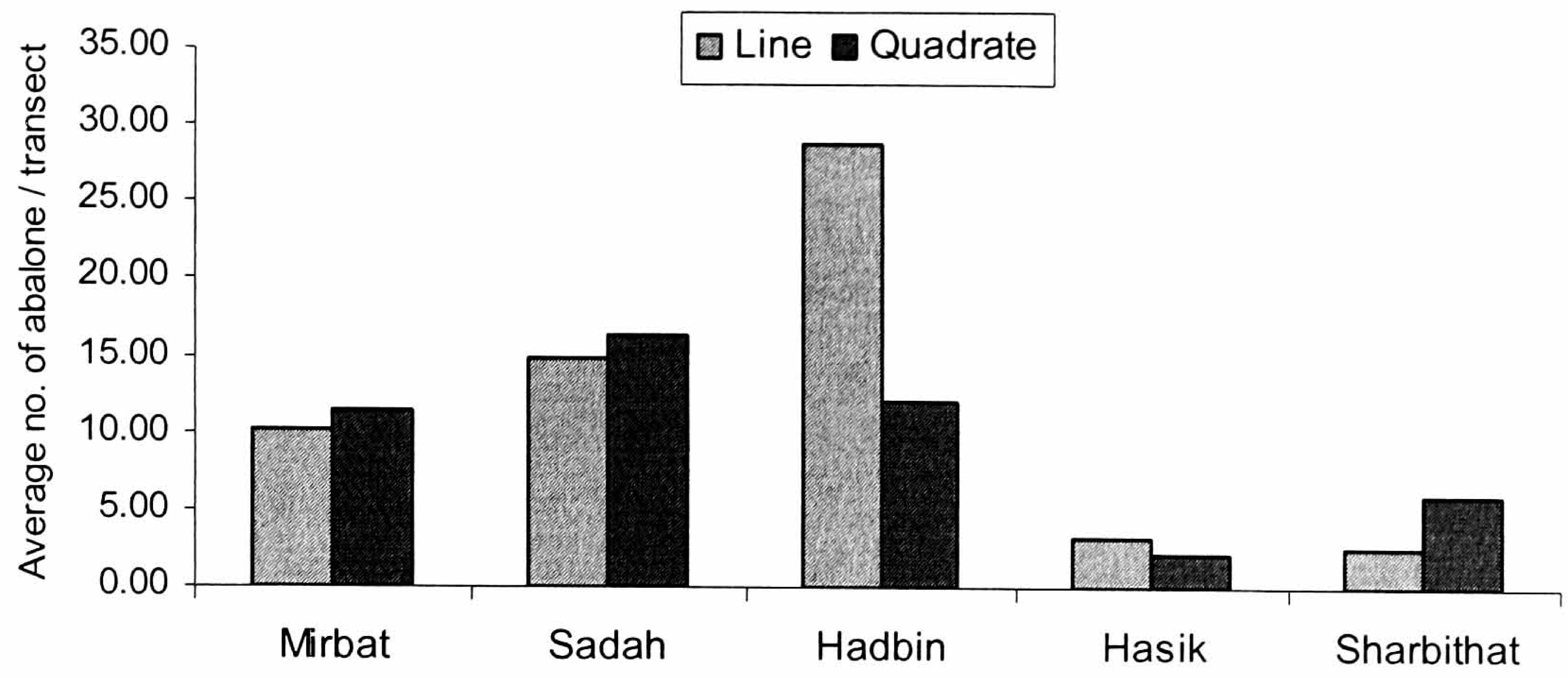


Figure 4.4 Average number of abalone per transect (320 m^2) and per quadrate (100 m^2) at the five main fishing areas

The density of abalone per square metre (m^2) varied between the two methods; the quadrate showed greater density of individuals per square metre than the transect line. That was because the quadrate survey was mostly conducted at depths between 0-10 m where the study showed latter much abundance of abalone, while the transect survey was conducted deeper, up to 20 m, in order to find out the abalone distribution at different depths.

The mean abundance of *Haliotis mariae* was 0.07 individuals/m^2, which is very low compared with abalone abundance of other fisheries world-wide (Officer, *etal*, 2001). Moreover, it was much less than their abundance reported by Sanders (1982), at an average of 0.205 individuals/m^2.

Haliotis mariae has a preference for shallow water (< 10 m). Its greatest abundance was associated with depths between 0-5 m and 5-10 m at all study areas. The abundance was nearly equal at both depth ranges at Mirbat, Sadah, and Hasik, but at Hadbin it was much more abundant below 5 m, at double the abundance of depth range 5-10 m. By contrast, Sharbithat had the lowest abundance at all depth ranges, and the abundance of abalone at below 5 m was less than that at more than 5 m. However, the abundance was very low at depths between 10-15 m in all areas. Deeper water below 15 m supported no or few abalone (Figure 4.5).

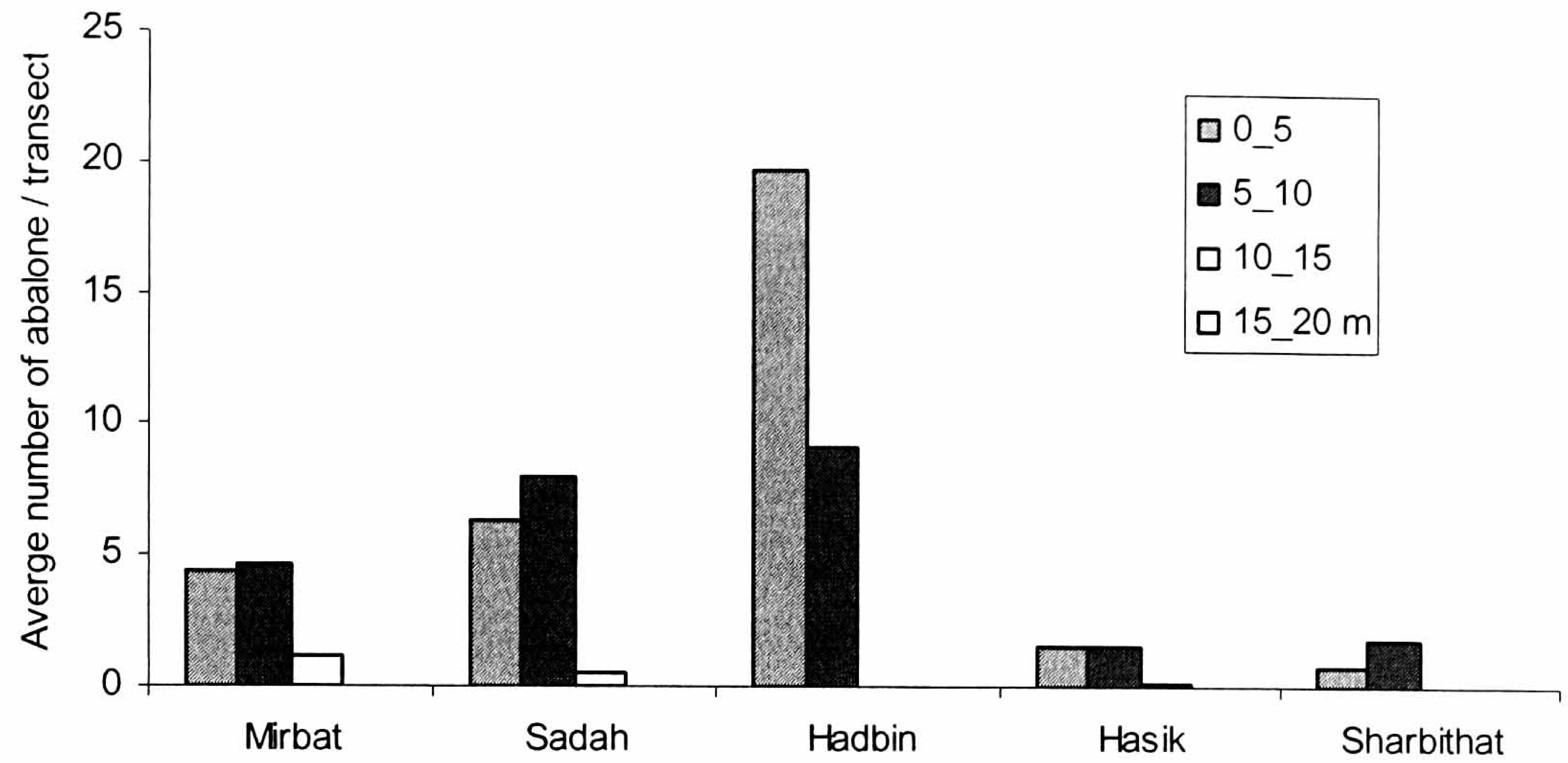


Figure 4.5 Abalone abundance at different depths (m) at the study areas.

The abundance of cryptic or juvenile *Haliotis mariae* varied among the five areas. Juvenile *Haliotis mariae* were more abundant in cryptic than in emergent habitat. However, in contrast to emergent abalone in Sharbithat, cryptic *Haliotis mariae* were observed abundant at Sadah and more abundant at Hadbin than emergent individuals. The abundance of *Haliotis mariae* varied among the five surveyed areas. They were much abundance at Hadbin, Sadah, and Mirbat, compared with Hasik and Sharbithat, where their abundance was very low. The mean sizes recorded were low in relation to the MLS (90 mm). Furthermore, *Haliotis mariae* was prevalent in cryptic rather than open habitat and did not form large patches.

The results gained from this survey suggest a decline in abalone abundance in all fishing areas along the study coast (Figure 4.6).

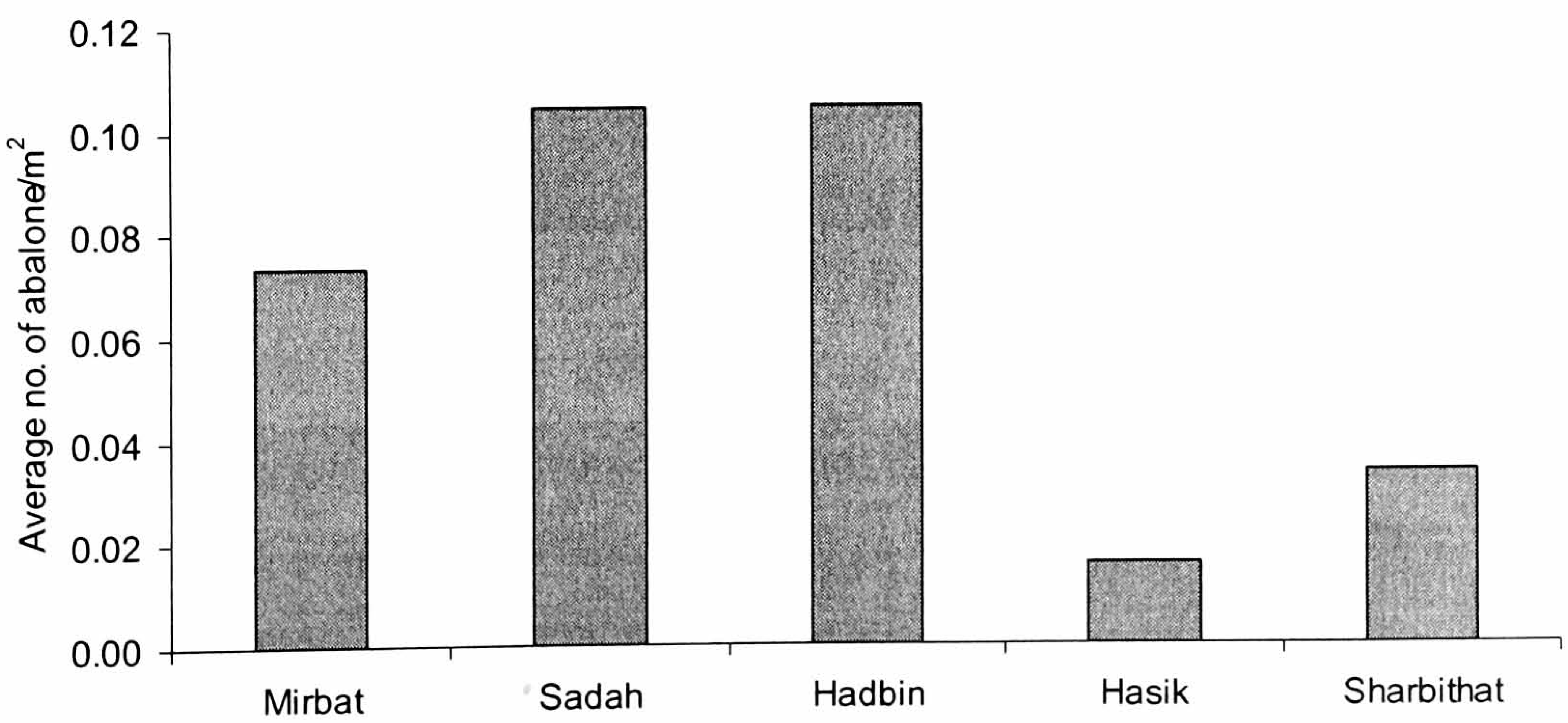


Figure 4.6 Distribution of abalone density at the five main fishing areas.

4.3.3 Habitat

The diving survey carried out obtained information on various fishing grounds and tried to determine available abalone habitat. The observation during this survey showed that abalone is found on rocky intertidal and subtidal areas. They occur attached to rocky substrate in areas with moderate water exchange, such as occurs on exposed or semi-exposed coasts, especially in waters with some waves or current action from the lower intertidal zone to at least 20 metres depth along the southern coast between Mirbat and Suqrah. In order to determine *Haliotis mariae*'s preferred habitat, an under water observation was made along the surveyed areas, together with the previously mentioned series of transects conducted during the survey at all areas. The reef of sea bed among the fishing grounds at Mirbat and Hasik consisted largely of flat rocks with some small and medium sized granite boulders (≤1-2m) distributed along the fishing grounds. In contrast a wide diversity of boulders was found at Sadah, Hadbin, and Sharbithat (≤1-5m) with some areas of flat rocks. Coral reefs covered little area at any of the sites (Figure 4.7)

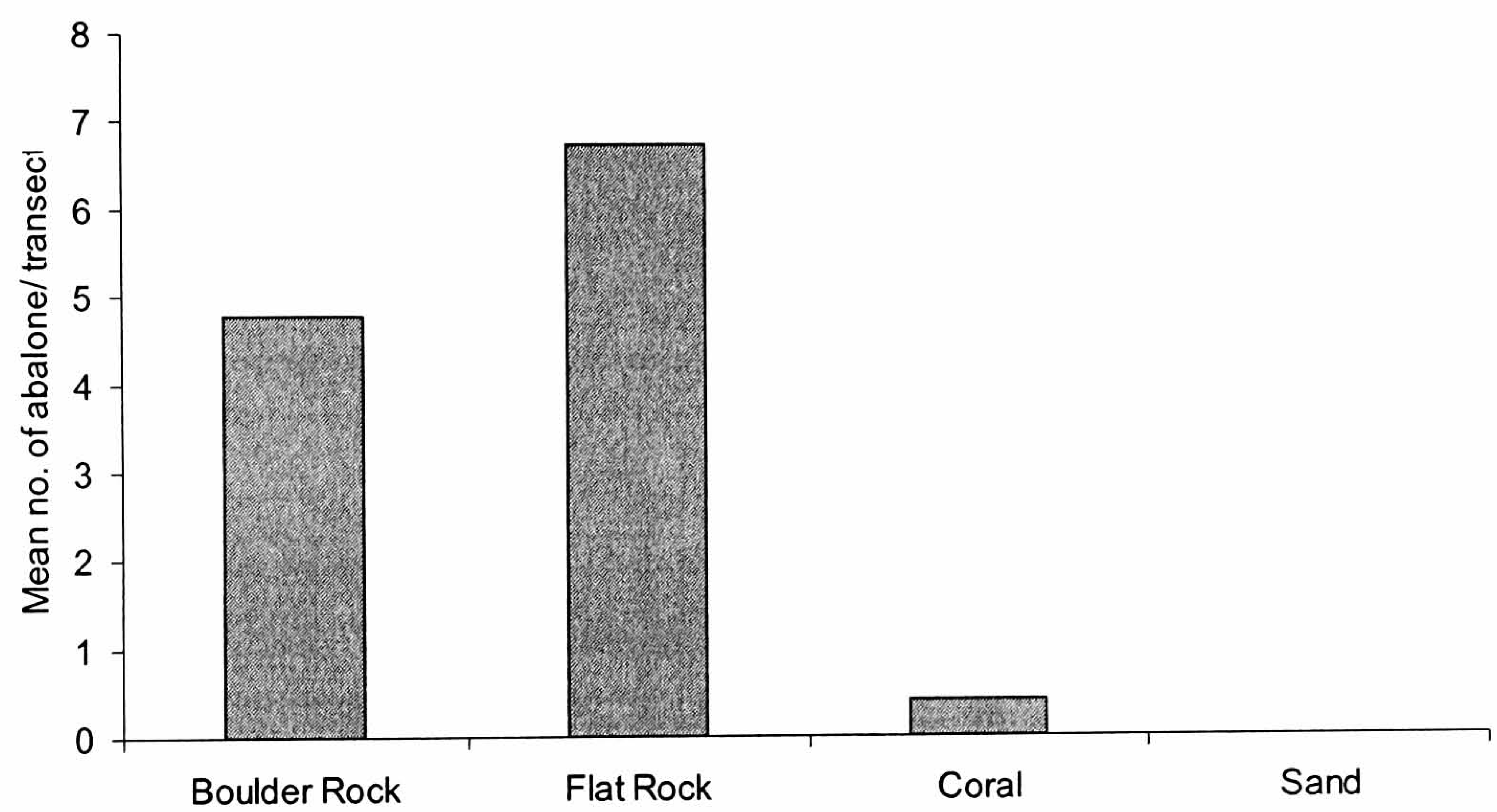


Figure 4.7 Distribution of abalone at different habitat

At the Mirbat fishing grounds, abalone was found at similar density associated with both granite boulders and flat rocks. However, few abalone were found attached to corals. Sadah and Sharbithat supports more on boulders than flat rocks. Abalone at Hadbin and Hasik was more associated with flat rocks than boulders, with some availability attached to corals at Hadbin. Thus, flat rocks with crevices appear preferable than rock boulders and corals in terms of suitability as habitat for abalone (Figure 4.8).

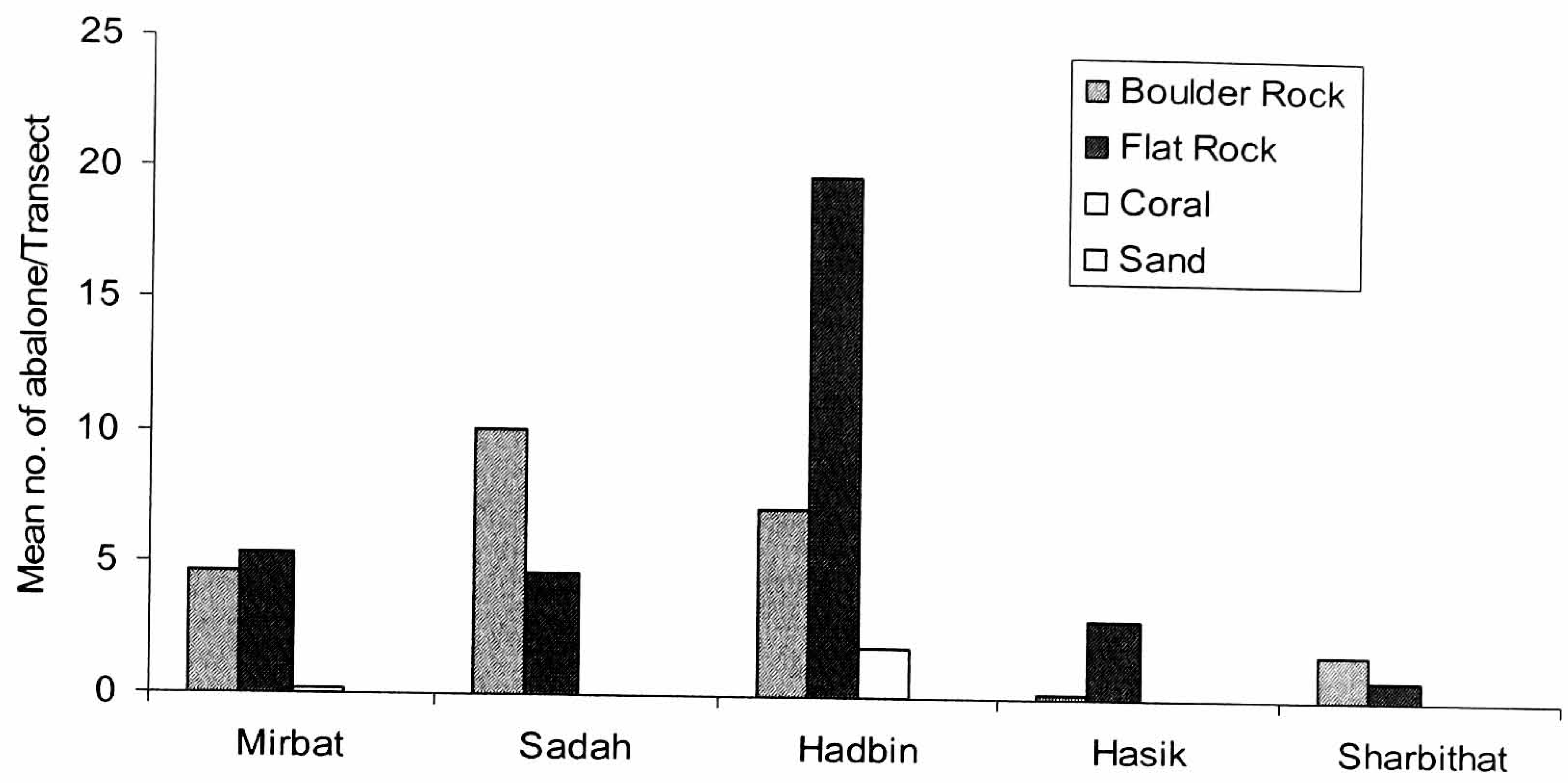


Figure 4.8 Distribution of abalone with different habitat at the study sites.

4.3.4 Competition

Abalone prefers a firm substrate, usually rock, and generally lives in crevices and under rocks or boulders. The adults graze on large marine brown algae such as kelp; they also feed on loose pieces drifting with the surge or current.

Abalone movement is very slow; they tend to stay at one location, and usually they hide in their crevices during the daytime waiting for food to drift by. However, they move when food becomes scarce for a long period. Juvenile abalone hide between urchin spines, and graze on rock encrusting coralline algae, diatoms, and on bacterial films. As they grow they increasingly rely on macroalgae.

Many competitors threaten abalone; the major one is sea urchin, which utilizes abalone food and living space. This might induce abalone to leave their crevices, or if they stay, mean less food is available. Despite the urchins' effect on abalone population, they are used as a shelter by juvenile abalone. This species has a wide ranging distribution throughout the whole coastline and is found in huge abundance. They attack plants when drift becomes scarce and destroy entire stands of algale. When they are in large numbers, they are able to prevent drifting food from reaching abalone crevices, or their density may even prevent abalone from moving out of these crevices. Ogawa (1994) reported that sea urchins were present at 6 times the individual density of abalone in the Omani wild fishery and they compete with abalone for food and living space. The density of sea urchin has increased rapidly, and the data gained from the survey during this study has indicated significant changes in their numbers around the fishing zone and that they are sharing the same habitat of abalone (Figure 4.9).

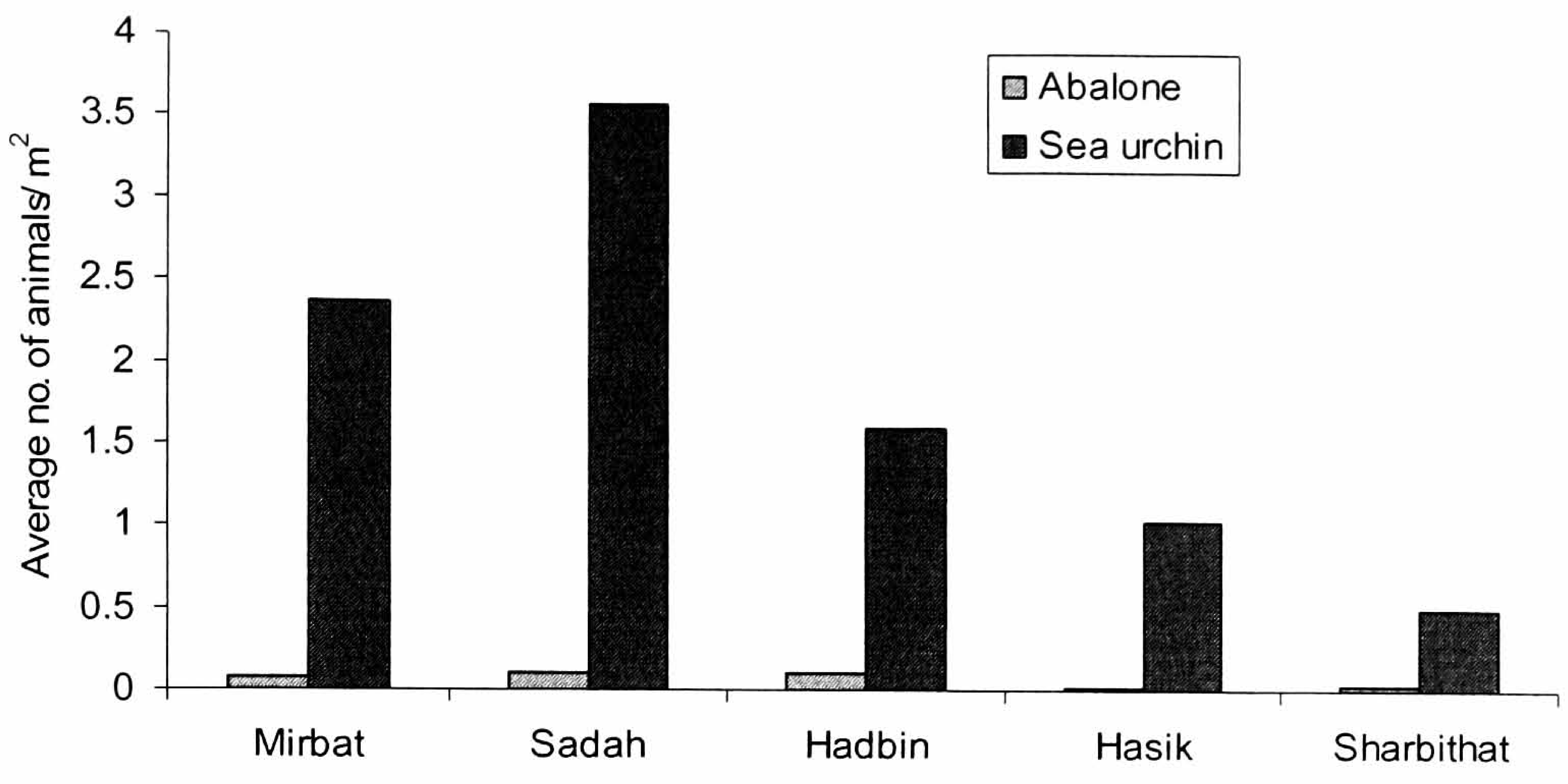


Figure 4.9 Abundance of abalone and Sea urchin at all areas

The highest density of sea urchin was recorded at Sadah area (3.5 individuals/m^2) following by Mirbat (2.3 individuals/m^2), whereas in Hadbin it was at 1.6 individuals /m^2. Hasik and Sharbithat support the lowest density of sea urchin, 1 individuals/m^2 and 0.49/m^2 respectively (Figure 4.10)

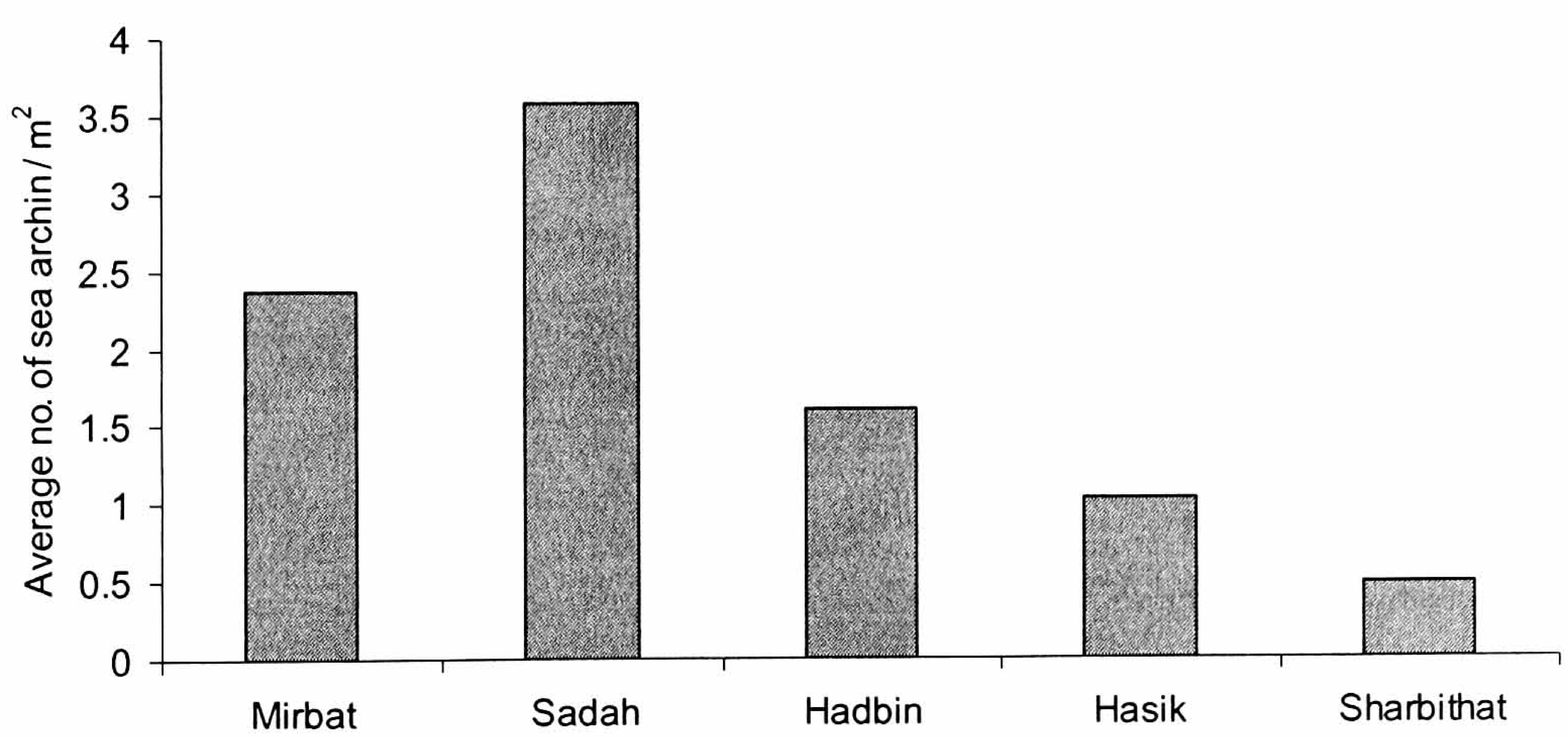


Figure 4.10 Average abundance of sea urchin at all sites

Their average density was 1.8 individuals/m^2 whereas abalone was 0.07 individual/ m^2, which is at about 25 times the individual density of the abalone.

4.3.5 Predators

A wide variety of organisms are known to prey on abalone (Tegner & Levin 1983). Larger abalone appear to be protected to some degree by size from most predators. The studies of the predators in the abalone habitat at all sites covered in this study showed various species of crustaceans, echinoderms, molluscs, fishes, and others associated with abalone and sharing the same habitat. Among the known abalone predators, some variation in the abundance of sea star, moray eel, octopus, and lobster was found at each area. These predators may have an effect on the population of *Haliotis mariae* throughout its life stages.

Sea star and moray eel were recorded at higher density at Mirbat, Sadah, and Hasik fishing grounds, than Hadbin and Sharbithat. However, octopus and lobster were present in low numbers. The latter is scarce because of this species has been over fished in the last few years. Figure 4.11 shows the distribution of sea star and moray in different abalone habitat.

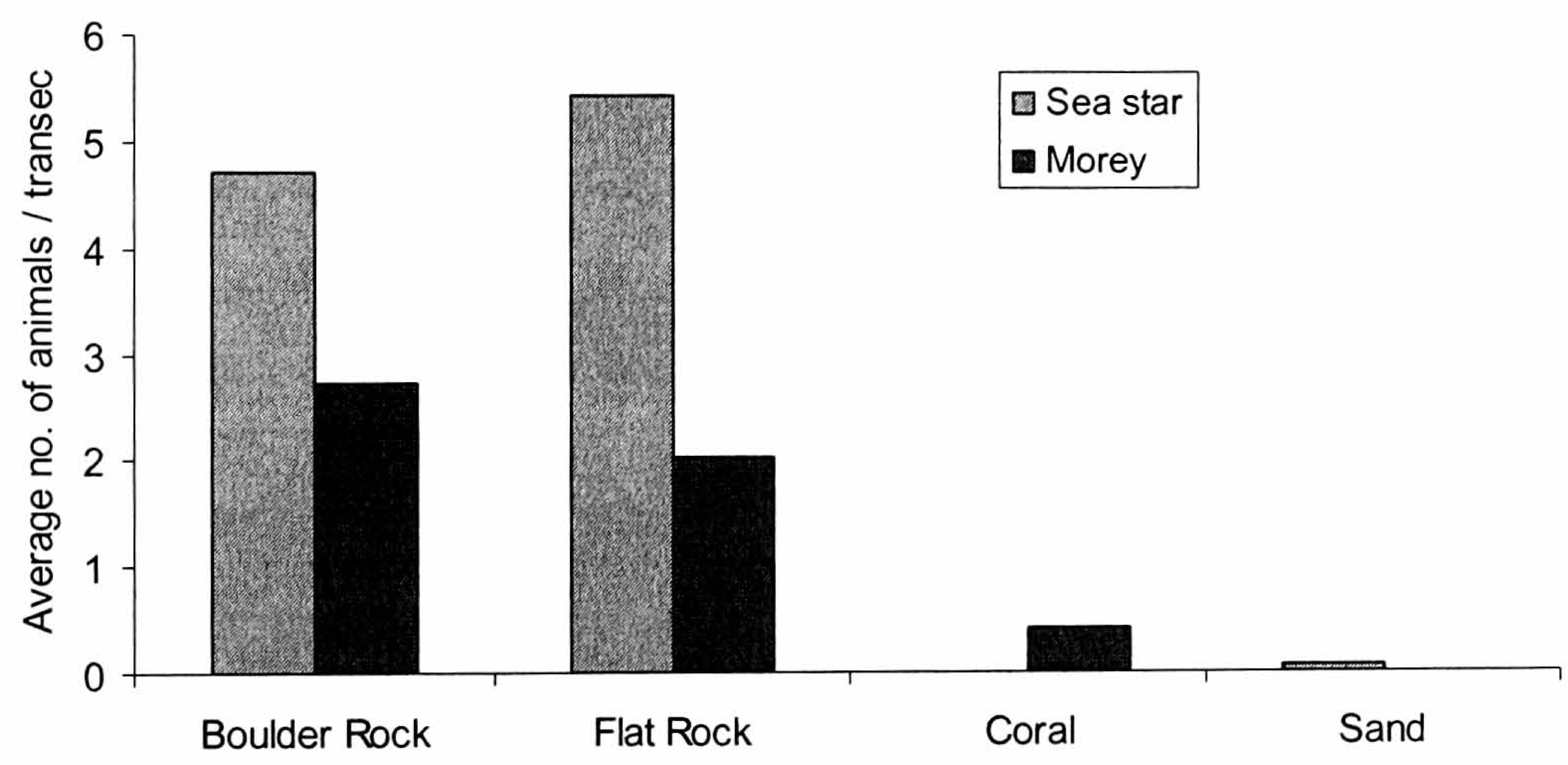


Figure 4.11 Main predators sharing different habitat with abalone

Ogawa (1994) indicated that during his diving around Sadah Bay during the diving season he observed many fishes, which can be considered as predators of abalone swarming around the abalone habitat. This could be a problem when divers turn over the boulders to search for abalone; small abalone and larvae become visible and accessible to these fish predators. Today, the number of divers and shore pickers has increased rapidly and this practice has become popular because of the scarcity of abalone. This will have an impact on the future of this resource.

4.4 Discussion

4.4.1 Geographical distribution

The known southern range of *Haliotis mariae* is limited and restricted to a short coastline extending between Mirbat and Sharbithat, but divers report that it may also be found as far east as around Souqrah. The distribution range has been mentioned in the few detailed studies available on this species: Waleed Associates, (1981) reported the distribution of *Haliotis mariae* to be between Mirbat and Hasik, which is the same range reported by Sanders (1982). Barratt *et al.* (1984) indicated its distribution between Mirbat and Sharbithat. Johnson & Shepherd (1992) reported that abalone is distributed from Mirbat to Hasik, around Al'Halaniyat Island, around the Sharbithat coast and as far as Masira Island. However, as this resource has been exploited for a long time, it is clear that it has disappeared in some of these areas, like Masira Island and Al'Halaniyat Island, while it is sharply declining in other areas like Mirbat. The bulk of the commercial catch is made in relatively small but obviously highly productive areas such as Hadbin and Sadah. It would seem that conditions in these areas are ideal for abalone.

This study tried to evaluate the current distribution of this species, to find out the factors controlling this distribution, and to confirm the status of the stock. As herbivorous gastropods are known to have controlling influence upon the zonal distribution of intertidal algae (Underwood, 1980), the limited distribution of abalone in the southern coast of Oman is closely linked to the similarly limited distribution of the algal communities dominated by the Kelp *Ecklonia radiata* and other brown algae along the coast between Mirbat and Sharbithat, which constitute a major food source of the abalone.

The extensive coralline algae along the coastline may be one of the most important factors governing recruitment to the population, and community distribution. Also, as large Haliotidae species are usually associated with warmer-temperature water, as in South Africa, South Australia, and Japan (Barratt *et al.,* 1984), the water temperature may be another factor which affects abalone distribution in southern Oman, where changes in current patterns and cooler waters resulting from the upwelling create a favorable environment. As the preferred habitat of abalone is in crevices and cracks, which are usually associated with rocky shores, this may be another factor that influences their distribution and restrection along this coastline (Figure 4.12).

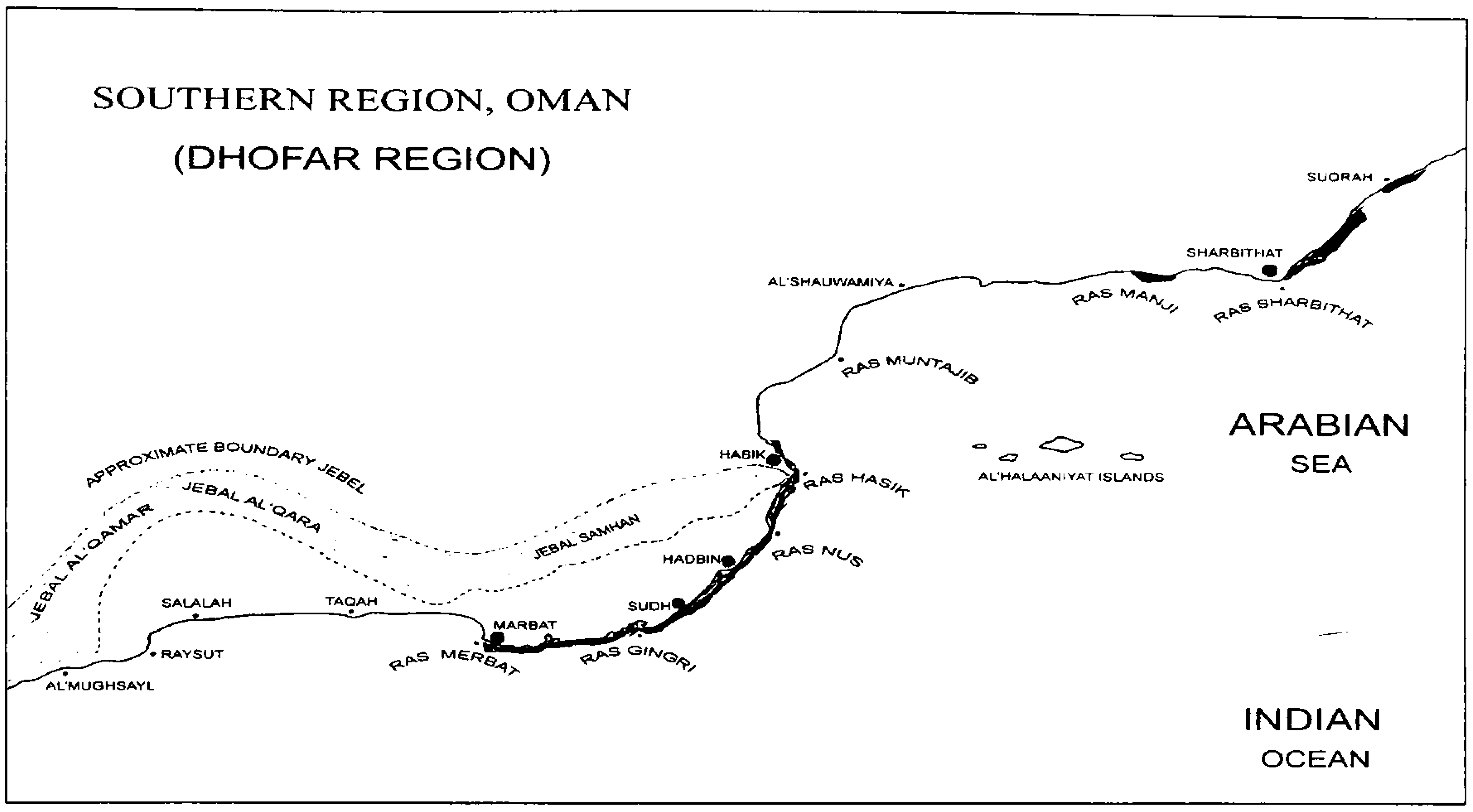


Figure 4.12 Current distribution of *Haliotis mariae* between Ras Mirbat and Suqrah at the southern coastline of Oman.

The heavy exploitation of this species during the last few years, without any attention being given to the stock status, has resulted in the recent low density, limited distribution, and the limited availability of the large sizes.

4.4.2 Abundance and stock estimation

The southern coastline has remarkable differences in topographic complexity which have been considered as factors causing differences in abalone abundance. However, although there were obvious differences in topography between the habitats surveyed in exposed areas (e.g. Sharbithat, smooth granite boulders; Mirbat, heterogeneous sandstone and flat rocks), the abundance of abalone was consistently low. With levels of recruitment to some populations of *Haliotis mariae* evidently low, heavy fishing during the last few years may have seriously depleted the stock. Populations such as at Hasik and Sharbithat had very low abundance of *Haliotis mariae*.

The total number of abalone taken during the survey represented the abundance of animals at the total area of seabed covered during this survey; on this basis the estimated mean density of abalone at these locations is 0.07 individuals / m^2.

Abalone individuals were observed at a shell length between 20.6 mm and 121.8 mm, but the mean sizes of all populations were below the MLS (90 mm). However, *Haliotis mariae* were scarce in Hasik and Sharbithat (only 32 and 34 individuals respectively were counted).

The abundance and size composition of *Haliotis mariae* varies over the areas covered in this survey. Variation in abundance, mean shell length, and juvenile abundance, are all important in determining the status of abalone stocks of *Haliotis mariae* and suggested a serious decline in this fishery.

The abalone density, together with the known of the area of the abalone producing reefs was used by Sanders (1982) to calculate the abalone stock for *Haliotis maria* at the southern coast of Oman. He concluded that the length of abalone producing reef between Ras Mirbat and Ras Noos was 86 km, and his estimate of the abundance of *Haliotis mariae* at all the fishing grounds was 1804,000 pieces. This abundance was higher than that reported by Waleed Associates (1981) in a survey of the fishing ground which produced an abundance estimate of some 1200,000 pieces.

The recent survey covered the same coastline as Sanders (1982) (86 km) and areas beyond that to the east of Ras Noos and around Sharbithat which was estimated to represent a further 15 km.

Tarr (1993) used the same method to estimate the stock of South Africa abalone *Haliotis midea* Linne. Following the procedure used by Tarr (1993) and Sanders (1982), the total length of the coastline which contains abalone producing reef along the whole coast was calculated at 101 km excluding Ash'Shawaimyah, as there is no abalone producing reef in this mid area. The width of the reef varied along the coastline, and was estimated at each surveyed site with an average of 100 m. On the assumption that the abundance of abalone in the unsurveyed areas is about the same as in the surveyed area and based on the observation presented above, the preliminary estimation of abalone abundance in the total fishing ground is about 707000 pieces (101 km×100×0.07). This estimation refers to the number of abalone available to divers, and not to the total number of the stock, as there are considerable numbers of small juvenile abalone which are unavailable because of their cryptic habit (Sanders, 1982). With reference to the overall average weight of foot muscle obtained in the monthly studies at 77.1 g/individual (see Chapter three). The stock number estimated above could be converted to 54.5 t of flesh (707000 pieces×77.1g). Given its high commercial value, and as *Haliotis mariae* supports an important fishery in the southern region of Oman, this abundance of *Haliotis mariae* is inadequate to support a good reproductive level and maintain a sustainable stock.

The annual landings by divers during the last few years varied between 28-55 t, which is close to this quantity (Al-Hafidh, 1999).

4.4.3 Habitat

Abalone prefers a particular habitat, which appears to be related to the availability of crevices between rocks and boulders associated with rocky shores. This is also related to availability of algal communities around these shores. Small abalone usually seek cover in crevices, and under rocks or boulders. This behaviour probably results from an instinctive attraction to dark places, which protects them from many predators. The rocky shores are ideal to provide such shelters. Though small abalone hide during daylight hours in their crevices or under the rocks, they are active at night. Large abalone seek cracks and crevices of rocks at open and more visible locations where food is more available. Usually the small abalone occur in the shallow waters between high and low tide whereas adult abalone have wide vertical distribution. They occur at the intertidal zone and up to depths below the low tide mark (< 20 metres). Abalone has their maximum population density at depths below 10 metres where seaweed and kelp beds, their natural food, grow abundantly.
Unfortunately, the observation along the coastline suggest that many abalone habitats are destroyed by bad practice of divers through the process of turning over the boulders when searching for the abalone. Degradation in the algal cover was observed along these habitats which could be related to the destruction of habitat and heavy grazing by dense sea urchin. This has altered large areas of abalone habitat. No indications of any pollution were observed along the surveyed area, as this fishery is located in remote areas where there are no industry effects on marine environment. The survey showed that much of the available reef habitat was unoccupied by *Haliotis mariae*.

4.4.4 Competition

Abalone and sea urchin prefer the rocky substrate, particularly crevices in surge channels, and avoid sand (Kato & Schroeter, 1985). In areas of high numbers of predators, abalone prefers narrow crevice habitats (Hines & Pearse, 1982). Abalone and sea urchin feed primarily on the same species of macroalgae (Leighton & Boolootian, 1963) and the latter have been described as potential competitors for food and living space (Tegner & Levin, 1982). Both abalone and sea urchin feed primarily on drift kelp, but sea urchin is known for its destructive grazing on attached plants when drift becomes limited. Abalone are fished intensively in this region, but there is no fishing operation for sea urchin. As a result, sea urchin are present in huge densities and sharing similar food and habitat along the five study areas. Abalone being restricted to crevices and cracks in low numbers, surrounded by a heavy density of sea urchin, may be prevented from reaching food sources, which leaves them in a precarious position.

This high density of sea urchin appears to be having a detrimental effect on abalone when food is limited, as well as on the algae communities and may be a major contributory to the reduction of abalone numbers. Moreover, it is causing injury to divers through the sharp spines when the divers place their hands between the rocks and inside the crevices to dislodge the abalone. Farther studies are required on this species as there is no specific information on sea urchin in Oman.

4.4.4.1 Isoyake

Isoyake is a phenomenon associated with rocky shores. It is the deterioration of food sources of abalone and other herbivorous invertebrate such as sea urchin, caused by heavy grazing of these animals, resulting in lack of algae and causing malnutrition (Karpov, 2001; Uchino *et al.*, 2004). Due to intensive and excessive grazing of these marine animals, the plumelet or the bud of macroalgae such as kelp which is considered as a favourite food for both species, is eaten up before the fronds are fully grown, although spores adhere to the surface of rocks and boulders under the water. This process affects the growth of kelp beds, and as a result, few macroalgae are observed over long periods of time (Ogawa, 1994).

This phenomenon has been observed extensively on the fishing ground by Ogawa, and he mentioned that one of the reasons for this phenomenon in the southern coast of Oman was excessive grazing by sea urchins, which were observed in huge numbers; six times those of abalone.

Many abalone habitats are without or with little and damaged algal cover in all the fishing sites covered in this study. Although, there are many possible causes of such habitat destruction, a likely cause is the heavy grazing by these two species associated with scarcity in food sources due to seasonality of algae and environmental changes, plus the rapid reproductivity and increase in the biomass of sea urchin in the study areas. Moreover, habitat destruction caused by divers through turning over the boulders when searching for abalone could be a factor contributing to this phenomenon.

4.4.5 Predators

Abalone has a flat, broad shell which provides great protection against predators, but because of their very slow movement, this makes them easy targets. Adult abalone tend to hide and stay in their preferred narrow crevices and caves between the rocks and under the boulders during the day time to avoid predation. Their movement increases in the night time when they start searching for food sources. Throughout their life, abalone contend with a variety of predators. At the early stages the eggs and larvae are consumed by filter-feeding fish and shellfish. Juveniles are attacked by nocturnal crabs, lobsters, gastropods, sea stars, octopuses, and fishes such as moray eel. Large abalone are not threatened by the predators of their early life, but larger and often more efficient predators become important. Big carnivorous fishes dislodge them from the rocks and swallow them whole or just eat the flesh. Storm-tossed rocks may crush abalone in shallow water during the monsoon rough sea. Only those in deep crevices or under large rocks will survive, and the more cryptically coloured individuals tend to survive longest. Among the predators recorded during this survey, sea star and moray eel probably have some effect on abalone population due to their large numbers in the fishing grounds, and because they share the same abalone habitat and live in crevices. Survey data on the distribution and abundance of abalone predators suggest some effect and predation damage on abalone. A significant relationship is found between the abundance of Sea star and availability of abalone, which may impact on the abalone stock. However, overfishing, turning over of boulders, and collecting small immature abalone are considered to have more impact on the sustainability of this fishery.

4.4.6 Monsoon effects on coastal waters and impact on abalone populations (Environmental changes observations)

The coastline in this region is known to be influenced by strong and persistent southwest monsoon winds. These replace the northeast winds, which prevail in the northern winter, resulting in a major reversal of the current system in the northern Indian Ocean. Full reversal of the current pattern is achieved over a period of four months (Luther *et al.*, 1985). Major changes in environmental conditions are created by this wind both on land and at sea.

The coastline during the period of monsoon between June and September each year is therefore subject to a seasonal rough sea and very severe ocean conditions, outflow from linked valleys along the coastline which contributes much fresh water and sediment during the rainy season, remarkable seasonal variation in water temperature, and the seasonality of algae with maximum development of the flora. These factors are thought to have some impact on the availability and distribution range of abalone. Changes in environmental conditions at the intertidal and subtidal zones occur largely as a result of upwelling of deep cold nutrient-rich water; water temperature decreases to 18 °C during this period. This decrease in water temperature is considered one of the main factors controlling the reproductive process. Thus, abalone reproduction may differ among years due to the monsoon strength. The upwelling areas are generally known as the most biologically productive areas, derived from the upwelling of nutrients into the euphotic zone from deeper, cooler water. Ryther *et al.*, (1966), Qasim (1977) and Smith (1984) described this phenomenon in the northwestern Indian Ocean. The latter mentioned that the productivity of the upwelling area of this region is equal in magnitude to the productivity of the Peruvian upwelling area.

Despite the seasonal productivity at this area, settlement of juvenile abalone is not successful every year and this may be due to bad sea conditions associated with adverse weather or severe currents in some years, which result in very few young (Johnson & Shepherd, 1992). The abalone population can normally adjust to this occasional failure. Being long-lived, parents can survive bad years and produce young in good years. But if those brood stock abalone are heavily fished every year, then after a bad year there may be very few surviving, and the population simply crashes. Large numbers of dead shells have been observed on the sea bottom of bays linked with major valleys each year after heavy rain and outflow. The divers also reported these mortalities during and after the monsoon season.

The sedimentation and organic materials brought from land to the littoral zone water during the rainy season, result in low oxygen levels in the semi-closed bays due to the decomposition of organic items. This is thought to influence the survival of abalone larvae, which are usually associated with the shallow waters. Growth and survival of early juveniles are known to be better in filtered water (Uchino *et al.*, 2004).

The water temperature dramatically drops from around 25 °C between October and May to 17 °C during the monsoon period between June and August each year, associated with the presence of oxygen poor water. This has been suggested as an environmental stress and as a possible cause behind the mass mortality of sardine (Indian Oil Sardine) which occurs each year along this coast (Sanders, 1982). Usually this mortality occurs mostly in the semi-closed bays along the coastline between Mirbat and Al'Gazar (Suqrah) (the abalone fishing ground range). In these shallow bays, immediately after such events, abalone have been found upside down and many dead shells distributed along the bottom. This annual phenomenon is known to the local people as "Ayed Al'aala". During the migration period of the sardine from the east to the west along the coastline, huge schools of sardine crowd these bays. This could be due to the drop in water temperature in the inshore water, and is associated with attacks by schools of big carnivorous fishes that push them to these closed bays. The fishermen keep watching along the coast for these events, and they collect the sardine and sun-dry them for feed for their cattle.

Although the upwelling waters are features on the entire coastline, small events of local intensity occur between Mirbat and Sharrbithat, which have particularly interesting floral and faunal communities. Barratt *et al.* (1984) revealed the presence of a unique macroalgal flora in the littoral and sub-littoral zones of the rocky segments of the Southern Oman Coast, which influences survival and availability of *Haliotis mariae* (Johnson *et al.*, 1992). However in the surveyed ground between Mirbat and Sharbithat, where the fishery is performed, brown and red algae and kelp cover, which are the main food sources of abalone are generally more scarce during the period February to July, and their density differs between sites, showing the highest level at Sadah and Hadbin.

The maximum development of the flora is apparently restricted to the monsoon season when upwelling is most pronounced, when the nutrients essential to the flora are available. Large brown algae are the major components of the sub-littoral flora along the coastline. These are represented by two species, one, common in the shallow sublittoral zone, is associated with *Sargassum*: the second, which dominates the deep sublittoral zone, is a kelp species, which has been reported in only three countries: New Zealand, Australia, and South Africa.

The kelp forest can be found along the coastline between Mirbat and Sharbithat for only a short period after the monsoon season, in contrast to all the up welling – induced kelp ecosystems known from other parts of the world, where these forests are found throughout the year. These algae communities are known to be highly productive, supplying cover and food for commercially important species such as abalone distributed in the intertidal and subtidal rocky shores along the coastline.

The abundance of algal species is highly seasonal, and standing crops are low relative to most of the sites. All these factors are associated with the monsoon season and contribute to the availability of this species.

4.4.7 Conclusion

The distribution of *Haliotis mariae* demonstrated by this survey suggests that this species is restricted to the rocky shores along the coastline between Ras Mirbat and Suqrah with the exception of Ash'Shuwaimyah coast. *Haliotis mariae* was found at more exposed shores, associated with the availability of macroalgale communities. They occur in a wide variety of habitats from intertidal to subtidal depths of 20 m, although most of the population is found in cryptic habitat between 5-10 m. The abundance of *Haliotis mariae* recorded was very low, which indicates the serious decline in the fishery. The density was found to be 0.07 individuals/m^2, and the available stock was calculated at 707000 pieces (54.5 t of flesh); this quantity is around the production of one season. The fishing grounds have been heavily fished since the start of the fishery, and the areas close to divers' homes or those with easy access show signs of heavy decline in the large sizes. The areas near Hadbin, Sadah and Mirbat show relatively more abundance compared with those around Sharbithat and Hasik, where *Haliotis mariae* was scarce.

The size composition of *Haliotis mariae* varies among the surveyed areas, but generally the remaining population was of small sizes, below the minimum legal size (90 mm SL). The present density is inadequate to support a good reproductive level and maintain a sustainable stock.

The survey of abalone habitats indicated that these habitats are mostly consist of boulders and flat rocks with crevices and cracks, but most of these habitats had been destroyed by bad practice of divers through turning over the boulders. Degradation in the algal cover was recorded at all the surveyed coasts, which might be a result of the habitat destruction.

Biological factors other than exploitation by divers and habitat destruction, such as competitors and predators, may have contributed to the decline of this fishery. Competition between sea urchin and abalone for living space and food sources was observed in the study areas. Heavy grazing of dense sea urchin on marcroalgale was recorded. This resulted in deteriorating algale sources (Isoyake phenomenon), which was observed and recorded at all the fishing grounds. The huge numbers of sea urchin may have contributed to abalone mortality within the abalone distribution range. The study of distribution and abundance of abalone predators suggests that sea star was the main predator present in the abalone habitat, which might lead to predation damage to the abalone population

This coastline is strongly affected by the monsoon which has some influence on the food availability as well as some impact on environmental changes. The fishery decline might also have resulted from large-scale oceanographic or ecosystem fluctuations caused by the monsoon. The survey observation indicated seasonall deposit of new empty shells in the semi-closed bays at some sites after flood events during and after the monsoon season. Also, mass mortality of sardine has been recorded in these bays, which is suggested to be as a result of environmental stress.

The results gained from this survey indicate that *Haliotis mariae* stock is seriously affected and the stock seems unlikely to be sustainable for long under the current fishing pressure combined with other influenctial factors.

CHAPTER 5

GENETIC DIVERGENCE OF *Haliotis mariae*

5.1 Introduction

Haliotis mariae Wood, 1828 has a limited distribution and is known to be the only Haliotida species inhabiting the Omani waters (Johnson *et al.* 1992). Recently this species has become overfished. In view of its commercial and scientific importance, and differences in the characteristics and morphology of the shells between different parts of its distribution range, it was considered necessary to determine whether genetically different stocks exist, as that would have implications for management actions. The aim of this study was to carry out a preliminary genetic characterization of *Haliotis mariae* and study the genetic diversity and population structure of this species at Mirbat, Hadbin and Sharbithat, to find the similarity or divergence of the abalone population in the three areas, and to obtain initial genetic data for management purposes. Moreover the genetic diversity of *Haliotis mariae* will be compared with the other known Haliotidae species found globally, to find any relationships among them.

5.2 Materials and Methods

In the genetic field, different methods have been used to resolve genetic relationships of various taxonomic groups at the species level: Mitochondrial DNA markers such as *16S ribosomal RNA* (*16S rRNA*) and cytochromee c oxidase subunit I gene (*COI*), nuclear DNA markers such as *18S ribosomal RNA* (*18S rRNA*), and the first internal transcribed spacer of *rRNA* (*ITS-1*) (Avis 1994; Hillis *et al.*, 1996). This study was based on sequence analysis in the Cytochrome C oxidase sub-unit I gene (CO1) and the Cytochrome B oxidase (CytB). The laboratory analysis was carried out by the Advanced Biotechnology Centre in Dubai (UAE).

5.2.1 Samples

Specimens of *Haliotis mariae* were caught from the wild stock of the southern coast of Oman during 2004. A total of 50 adult individuals were sampled from each locality, i.e. Mirbat, Hadbin and Sharbithat (borders and middle fishery zones), and the samples were brought alive to Mirbat Abalone Seed Production Station. The foot muscles were removed from the shell and individually numbered and stored in a freezer at -80 °C prior to being transported frozen to the Advanced Biotechnology Centre at Dubai (UAE) on dry ice (frozen CO_2). The samples were named by taking the initial letter of the place of sampling and numbered accordingly, i.e. M1-M50 (Mirbat samples 1 to 50), H1-H50 (Hadbin samples 1 to 50) and S1-S50 (Sharbithat samples 1 to 50).

5.2.2 DNA extraction

Total DNA of the sample was extracted from the adductor muscle of each abalone sample using the phenol-Chloroform-isoamyl alcohol method (Klinbunga, 1996, 2003). Briefly the shredded muscles were incubated at 56°C for 2 hr with the DNA extraction buffer (10mM Tris, 100mM EDTA, 2% SDS pH 8.0) and Proteinase K (20 mg/mL). The DNA was extracted twice with phenol:chloroform:isoamyl alcohol (25:24:1) and precipitated using 100% ethanol and 2M Na-acetate. The DNA was dissolved in 50 µL of $Tris_{0.1}$.

5.2.3 PCR amplification of the CO1 sequences

The mtCO1 gene was amplified using primers from previously published data for the Abalone (Metz *et al.,* 1998) F1 (TGATCCGGCTTAGTCGGAACTGC) and R1 (GATGTGTTGAAATTACGGTCGGT). The PCR reaction contained 12.5 µL of AmpliTaq Gold PCR mix (Applied Biosystems) in 1X concentration, 1 µL of each forward and reverse primer (10µM), 100 ng of DNA and volume of the PCR was adjusted to 25 µL by adding deionized water. The PCR reaction was performed using ABI 9700 thermal cycler using the cycling condition; 95°C for 13 min., then 35 cyles of 94°C for 30 sec, 53°C for 30sec, 72°C for 1 min. The 580 bp product was identified by running 1% Agarose gel electrophoresis.

5.2.4 PCR amplification of the CytB sequences

For the amplification for the CytB sequences a Nested PCR using the two sets of primers was performed from the previously published primer sequences (Merritt *et al.*, 1998). In the first round UCYTB144F (5'- TGA GSN CAR ATG TCN TWY TG-3') and UCYTB272R (5'- GCR AAN AGR AAR TAC CAY TC-3') were used. The PCR reaction contained 25µL of AmpliTaq Gold PCR mix (Applied Biosystems) in 1X concentration, 2 µL of each forward and reverse primer (10 pm/µL), 2 µL of 25 mM $MgCl_2$ and 100 ng of DNA and volume of the PCR was adjusted to 50 μL by adding deionized water. The PCR reaction was performed using ABI 9700 thermal cycler using the cycling condition; 95°C for 13min., then 40 cycles of 94°C for 1min, 48°C for 1 min, 72°C for 1 min, hold 72°C for 30 min. The ~370bp product was identified by running 2% Agarose gel electrophoresis. For the second round PCR the primers used were UCYTB151F (5'- TGT GGR GCN ACY GTW ATY ACT AA-3') and UCYTB270R (5'-AAN AGG AAR TAY CAY TAN GGY TG-3'). For performing the PCR, 5 μL of the first round was mixed with the PCR reaction mix under the same cycling condition as for the first round.

5.2.5 PCR cleanup

The PCR product was cleaned using the enzymes Exonuclease and Shrimp alkaline Phosphatase (USB, USA). Briefly 10 μL of the PCR product was treated with 1 μL of the EXOSAP, incubated at 37°C for 2 hr and then enzymes were inactivated by heating at 85°C for 15 min. The product was clean PCR reaction for sequencing.

5.2.6 DNA Sequencing and Clean-up

Sequencing of both the CO1 and CytB regions was performed using the Bigdye v3.1 ready reaction mix from Applied Biosystems. Both the forward and reverse primers were sequenced for greatest confidence on sequencing. For sequencing the CO1 region 4 pm of each primer and 20 ng of DNA was mixed with the Bigdye ready reaction mix v3.1 and sequencing was performed as per the sequencing protocol using the cycling condition; 95°C for 2 min, then 25 cycles of 96°C for 10 sec, 50°C for 5 sec and 60°C for 4 min. For sequencing the CytB region the second round DNA amplification product was used. The primer concentration was adjusted to 2 pmoles and the reaction was performed using the cycling condition: 94°C for 2 min, then 30 cycles of 94°C for 15 sec, 48°C for 1min and 60°C for 1 min. The sequenced product was cleaned using the Ethanol-Na-Acetate and EDTA precipitation using the ABI, BigDye terminator cycle sequencing clean-up protocol. The electrophoresis of the clean sequenced product was performed using the ABI 3100 Avant (Applied Biosystems) as per standard procedure.

5.2.7 Sequence analysis

All the sequences were aligned in the CLUSTAL format and analysed using the MEGA v3.0 software. The genomic distances were calculated using the Kimura-2-

Parameters (Kimura, 1980), and the phylogenetic relationship was determined by the Neighbor-Joining method (Saitou & Nei, 1987) using the Bioedit software V7.0.0 in constructing the dendrogram. The tree was viewed using the TreeView software v1.6.6.

5.3 Results

A total of 150 abalone samples from three different places, Mirbat, Hadbin and Sharbithat in Oman, were sequenced in the Cytochrome C- Oxidase subunit I (CO1) and the Cytochrome B (CytB) region to determine the phylogenetic relationships.

5.3.1 Comparison of the samples within each of the sites

5.3.1.1 Mirbat

The phylogenetic relationships of the *Haliotis mariae* samples in the CO1 and CytB region of the genome obtained from the Mirbat area are shown in Figures 5.1 and 5.2 respectively. The genetic distances in both the region of the genome were found to be <2% and hence they cluster in one group. Samples e.g. M9, M11, M17 etc. clustered to 100% sequence similarity in both the regions sequenced (Figures 5.1 & 5.2). In contrast, samples e.g. M5 and M31 showed 100% sequence similarity in the CO1 region but differed by more than 1% in the CytB region. Similarly, samples M6, M49, and M24 differed by >1% in the CytB region but showed 100% sequence similarity in the CO1 region. The majority of the samples showed the same pattern of sequences in both regions of the genome.

5.3.1.2 Hadbin

The genomic distances calculated for the CO1 and the CytB regions sequenced in the 50 samples from Hadbin were < 2%, indicating that they are linked to each other belonging to one lineage (Figures. 5.3 & 5.4). Close analysis of both data sets reveals that samples showing the 100% sequence similarity in the CO1 region also showed the same relationship in the CytB region, whereas the samples showing 100% sequence similarity for CytB differed in the COl. For example, samples H1 and H39 are 100% similar in both regions whereas samples H25, H31, H50 and H22, showing 100% sequence similarity in the CytB region, diverged in the CO1 region with more than 1% sequence variation.

5.3.1.3 Sharbithat

The genomic distances calculated in the CO1 and CytB regions of the genome obtained from the Sharbithat samples were < 2% and hence they belong to one group (Figures. 5.5 and 5.6). The dendrograms (Figures 5.5 and 5.6) show that the samples S10, S12, S19, S32 clusterd to 100% in the CO1 region also clustered similarly in the CytB region, whereas samples S45, S30 and S43 showing 100% sequence similarity in the CO1 region differed by >1% in the CytB region. The samples S39, S23 and S37 clustering 100% in the CytB region showed >1% sequence divergence in the CO1 region. However, the majority of the Sharbithat samples showed the same clustering pattern in both genomic regions.

5.3.2 Comparison of all the samples of the three areas

The combined genetic distances in the CO1 and CytB regions for all the 150 samples sequenced in both regions was ≤ 2% (Figures 5.7 and 5.8); hence all the abalone samples from three different areas of Oman can be grouped with only slight variation in the genetic make-up. As the majority of the samples from all the three stations show 100% sequence similarities in both the regions sequenced, this suggests there is no genetic divergence between the areas. Closer examination of the data showed that samples H3 and H21 from Hadbin station diverged with more than 3% sequence variation for the CytB, but the same samples showed less than 2% sequence divergence in the CO1 region.

5.3.3 Comparison of samples from a single area with internationally published species using CO1 sequences

Figures 5.9, 5.10 and 5.11 represent the phylogenetic relationship of the Mirbat, Hadbin and Sharbithat areas with internationally published data in the CO1 region of the genome. The reference strains *Haliotis discus* (AY 146398), *Haliotis corrugate* (AY 679070) *Haliotis rufescens* (AF60843) *Haliotis tuberculata* (AY377729) and *Haliotis iris* (AF 060854) were downloaded from the GeneBank (See appendix). All three areas show vast divergence in the sequences, with the genetic distance between 25-40%, indicating that the species found in Oman is of a different genetic make-up than found elsewhere in the world. The closest relative for all the three places was the *tuberculata* species found in the Mediterranean region, with a sequence divergence of 25-27%. No close match for the *Haliotis mariae* species was detected in the GeneBank analysis and hence it can be predicted that no sequence data are available for the present species and this is the first attempt to sequence this species exclusively found in the Oman region.

5.4 Discussion

Haliotis mariae has for a long time been recognized to be the only Haliotidae species occurring in the Omani waters. Based on the monthly sampling during the period of the abalone project, some morphology differences were observed in the shell shape and thickness. Individuals between the three sites appeared to be different on the basis of shell characteristics. The shells of the abalone samples collected from Sharbithat are thicker, with minor difference in their shape from those of Hadbin and Mirbat. These differences suggest the importance of genetic studies to find divergence of the abalone among the three areas. Moreover, no previous genetic studies had been carried out on Oman abalone.

The results show a lack of genetic divergence between the three sites based on the mitochondrial DNA (cytochrome oxidase I (COI) gene). Sequences of COI and Cyt B are almost identical between the three populations. The sequence comparison of the 150 samples of *Haliotis mariae* in the Cytochrome C oxidase sub-unit I and the Cytochrome B oxidase region indicates that all the three populations are genetically linked, as the genetic diversity was within the 2% range in both genomic areas. There was a considerable homology in the sequences of all the animals found in the three selected areas of Oman (Figures 5.9, 5.10 and 5.11). Phylogenetic analysis showed that the individual haplotypes of each site are not separated into distinct clades, indicating high genetic similarity between the populations at the three study areas.

As a consequence, the abalone at the three sites should be treated as one stock and managed as such. It appears that there is no isolation of the stocks at each location and mixing, probably at the juvenile spat stages, occurs. To assess this there is a need examine water currents and dispersion patterns of spat. To this end, it is critical that no development that could disrupt these dispersion processes take place, for example building of islands or offshore facilities for the oil industry.

Comparing the data of *Haliotis mariae* from the three regions of Oman, i.e. Mirbat, Hadbin and Sharbithat, with published data from around the world, indicate that there is high genomic diversity with the other species. The results that confirm this study is the first attempt to characterize genetically the *Haliotis mariae* species globally. More studies need to be performed to investigate the genetic differentiation of the *Haliotis mariae* populations within their geographical range using other genetic methods (Chu *et al.*, 2003) to elucidate their evolutionary relationship and taxonomic status. The results would be useful for the management and protection of this species. However, the results of this study will serve as the basis for future genetic studies.

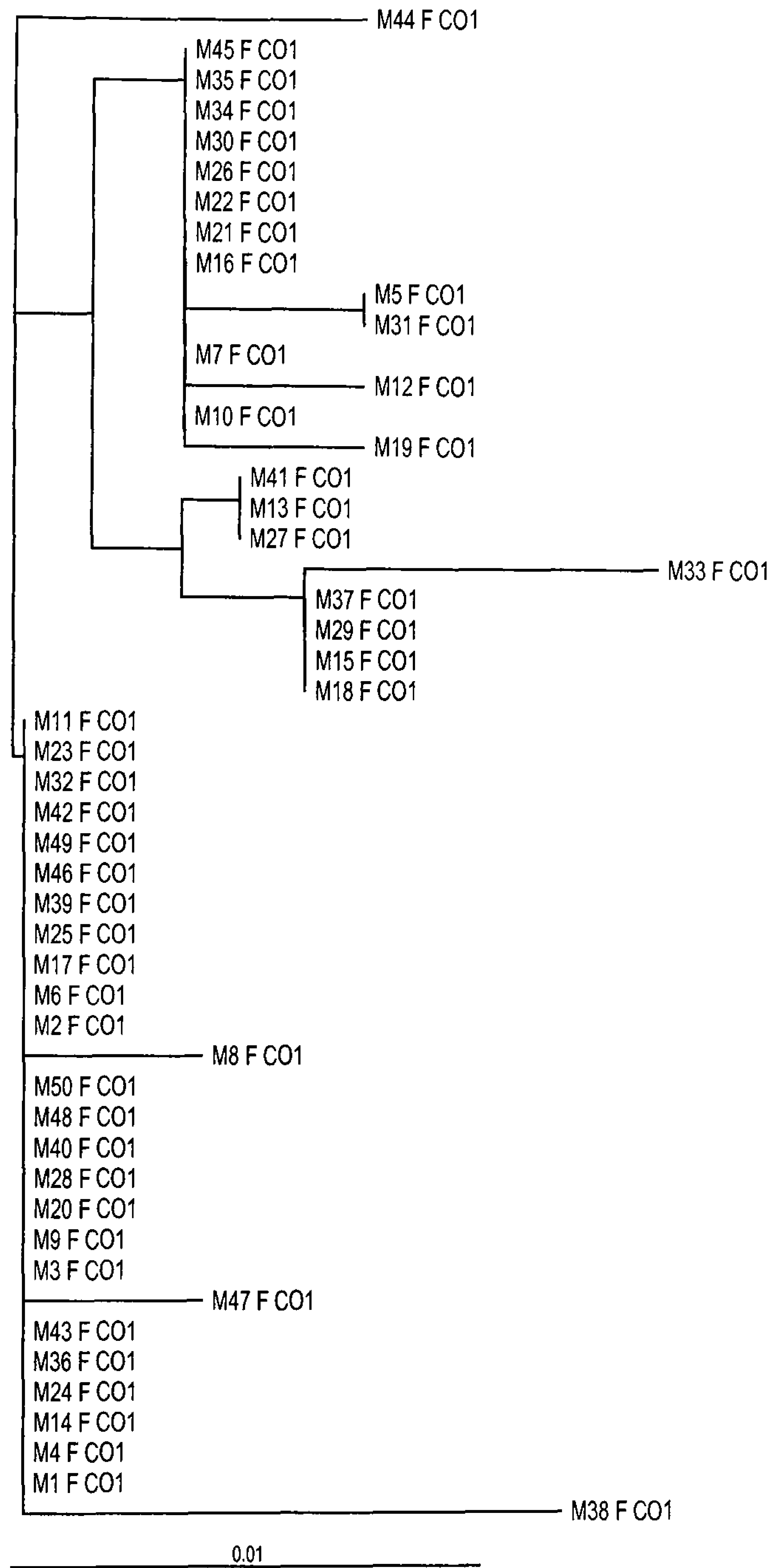


Figure 5.1 Mirbat samples showing Phylogenetic relationship in the CO1 region.

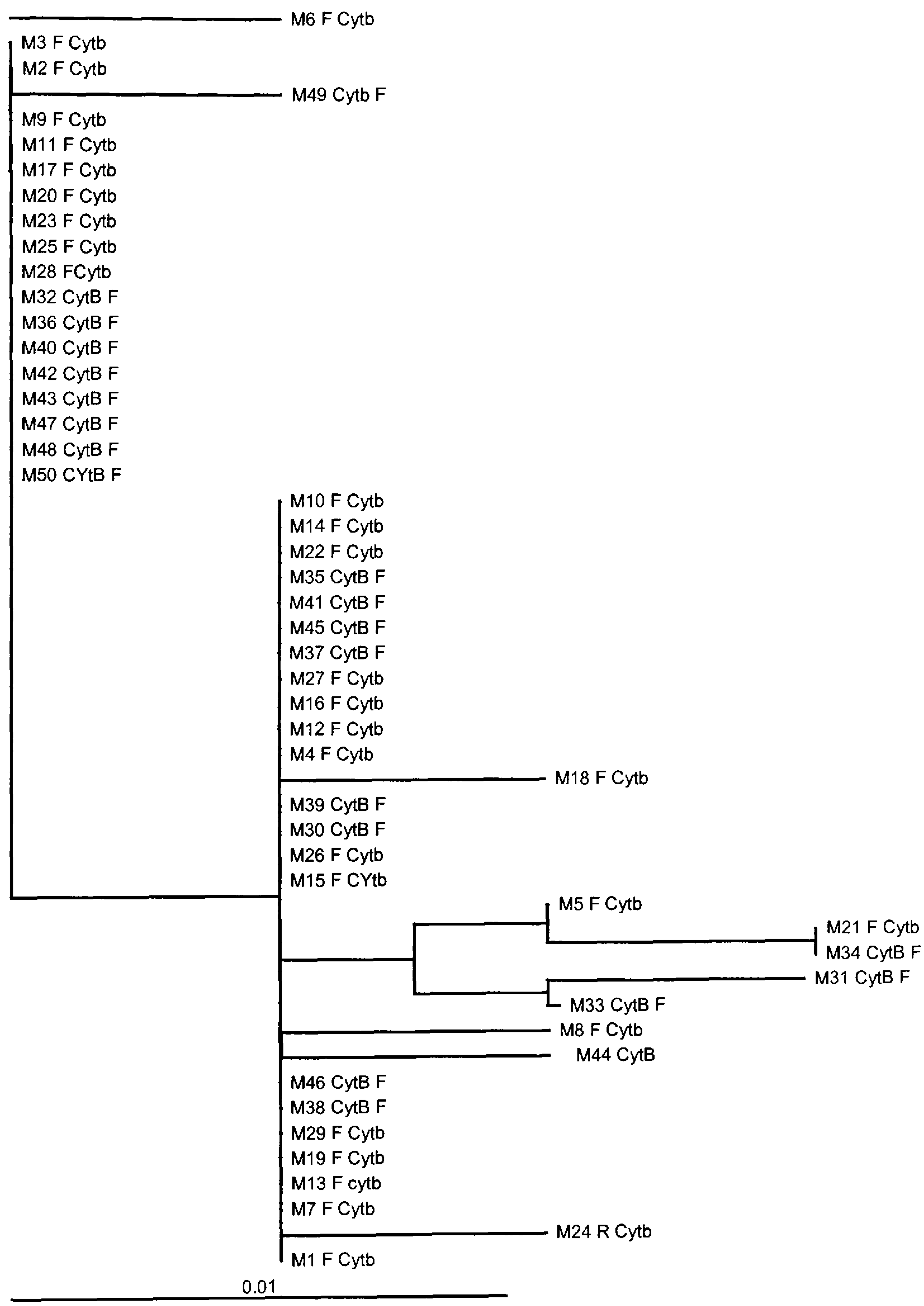


Figure 5.2 Mirbat samples showing Phylogenetic relationship in the Cytb region.

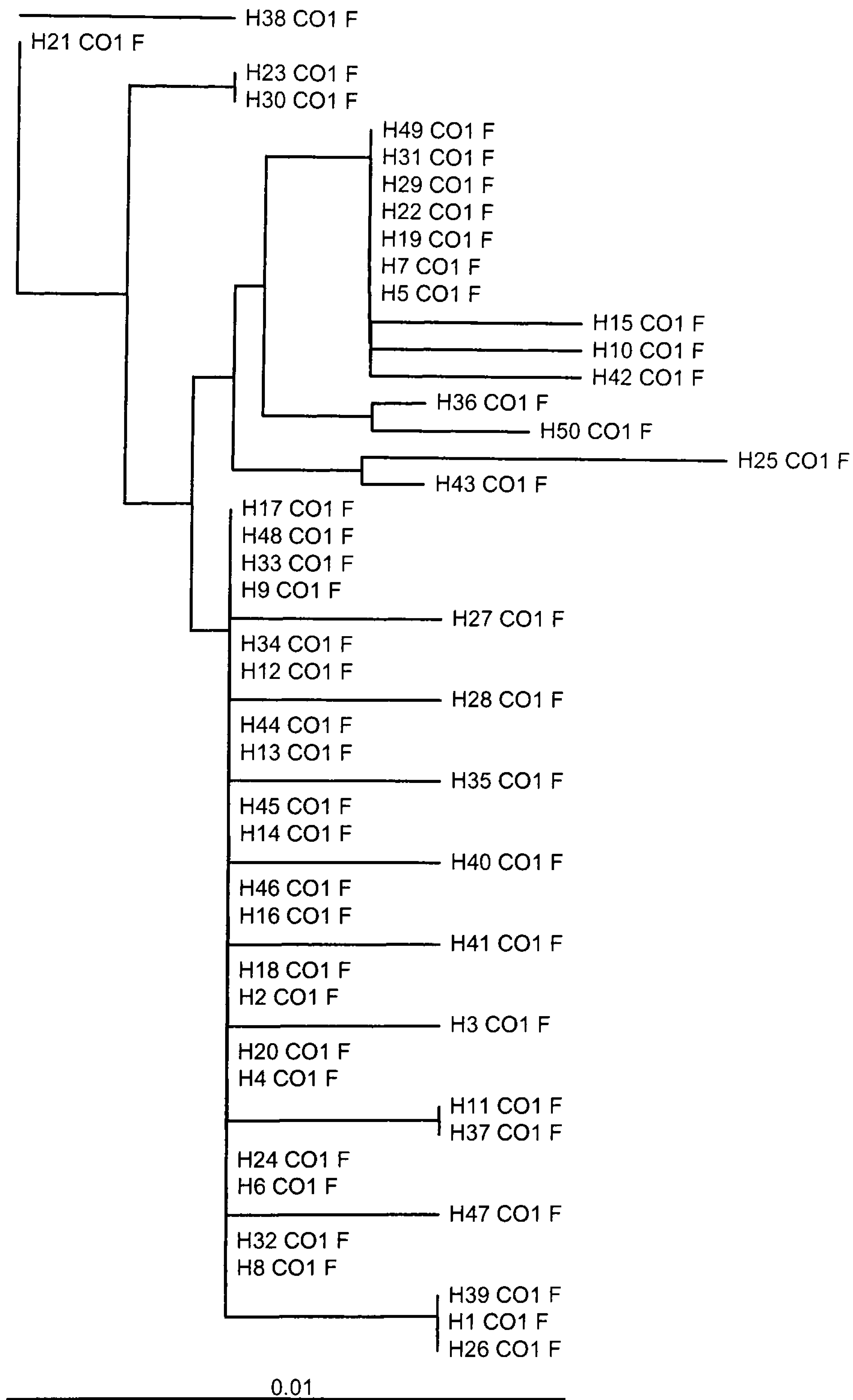


Figure 5.3 Hadbin samples showing Phylogenetic relationship in the CO1 region.

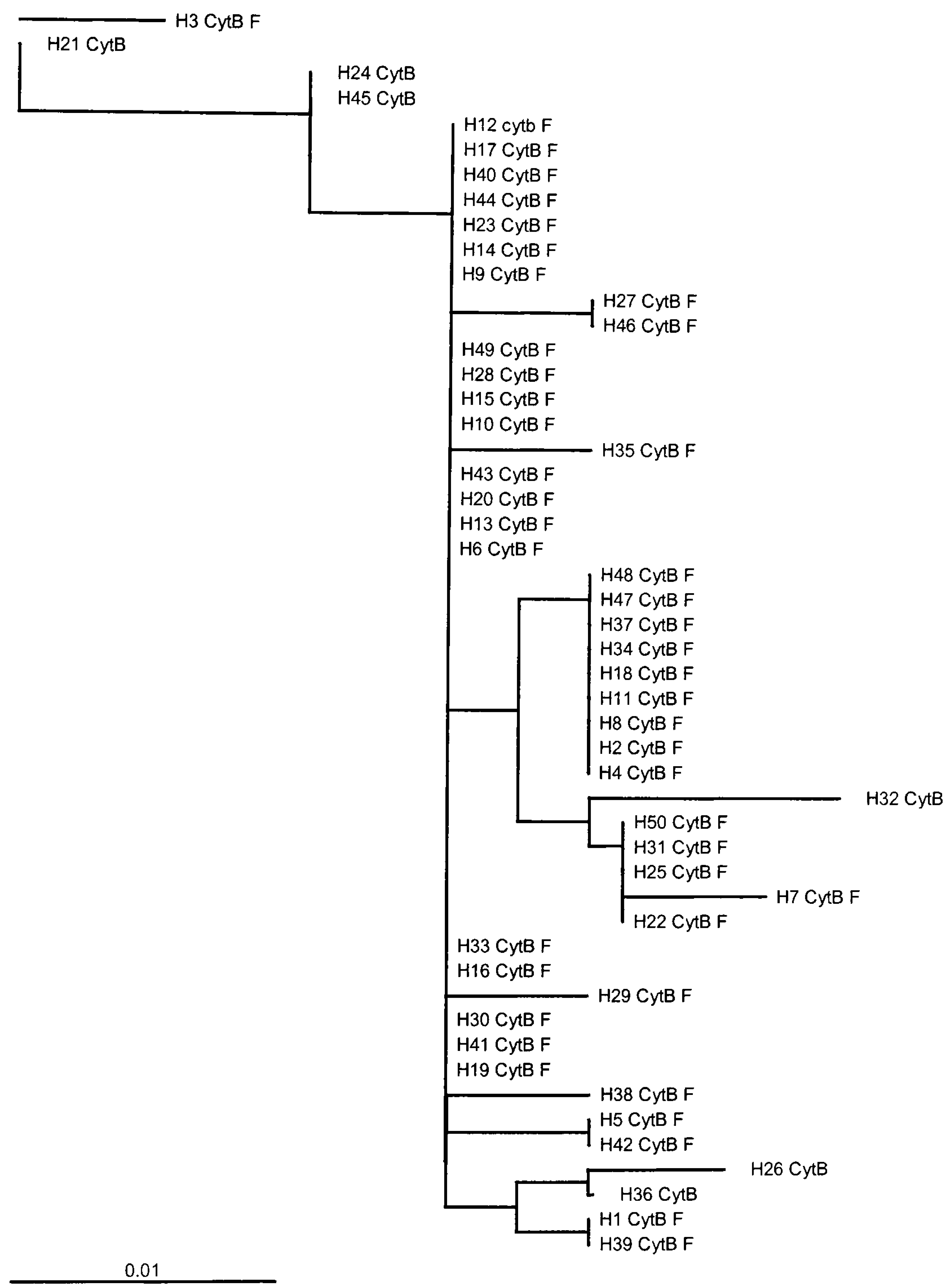


Figure 5.4 Hadbin samples showing Phylogenetic relationship in the Cytb region.

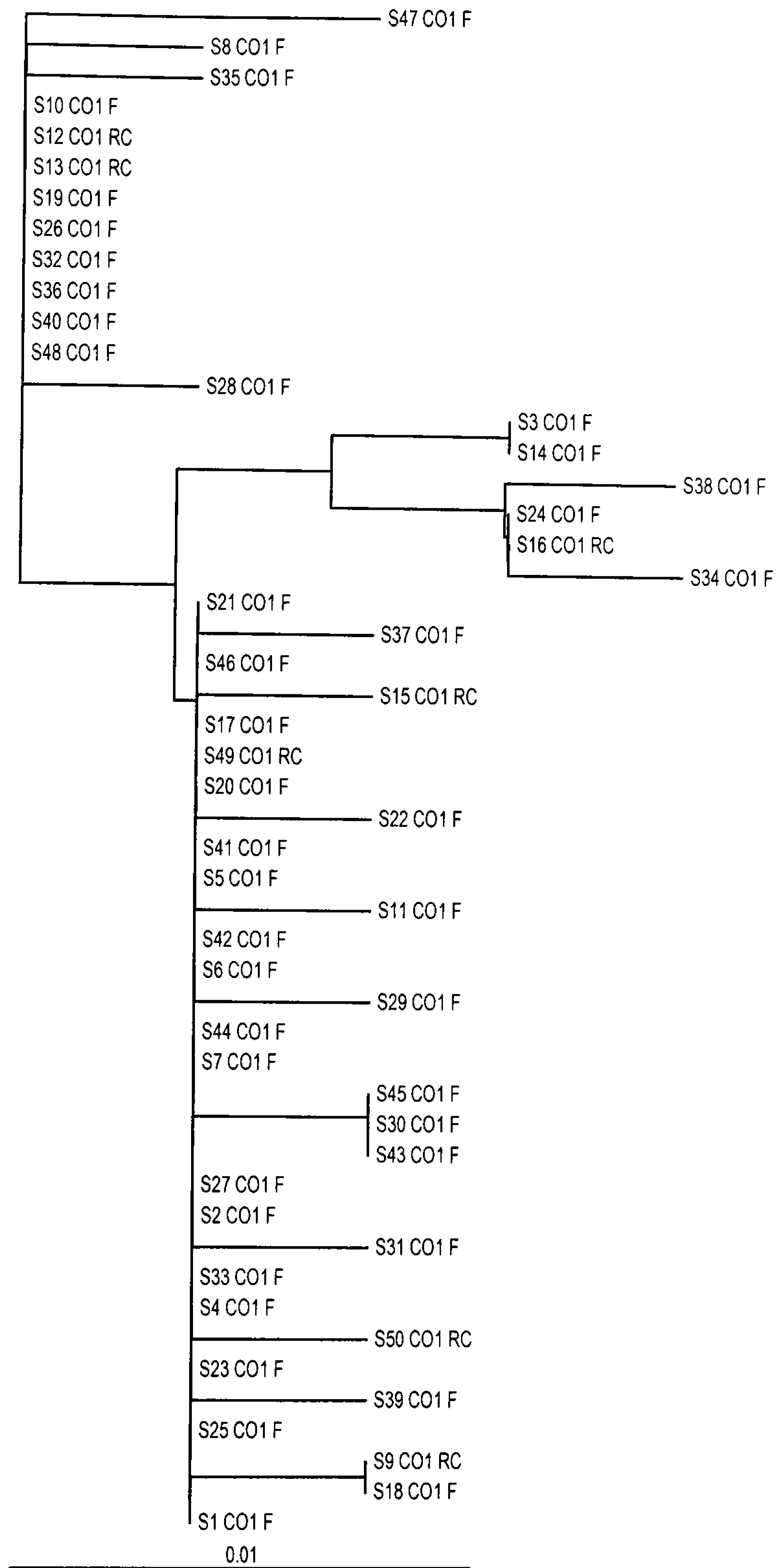


Figure 5.5 Sharbithat samples showing Phylogenetic relationship in the CO1 region.

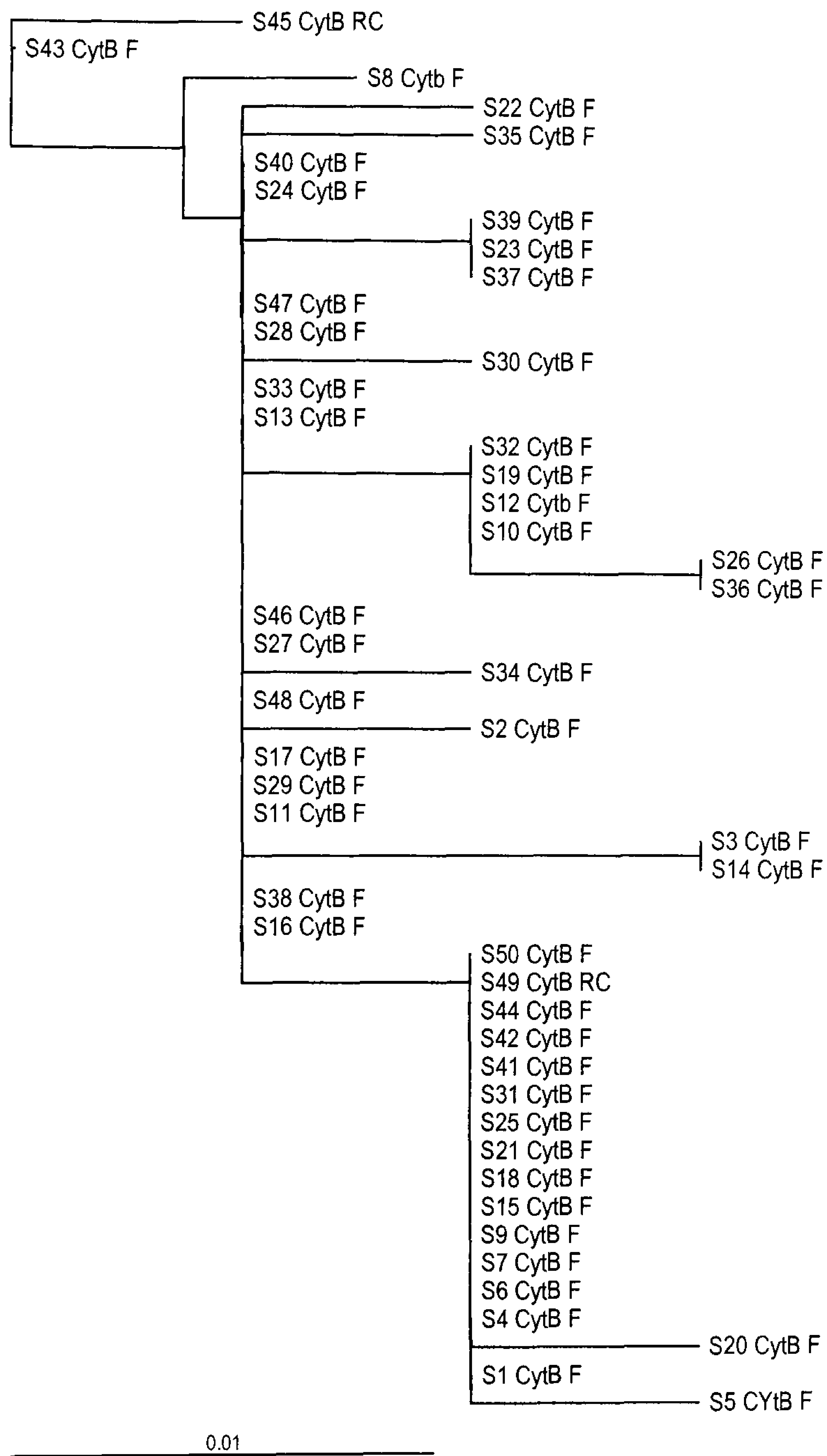


Figure 5.6 Sharbithat samples showing phylogenetic relationship in the Cyt B region

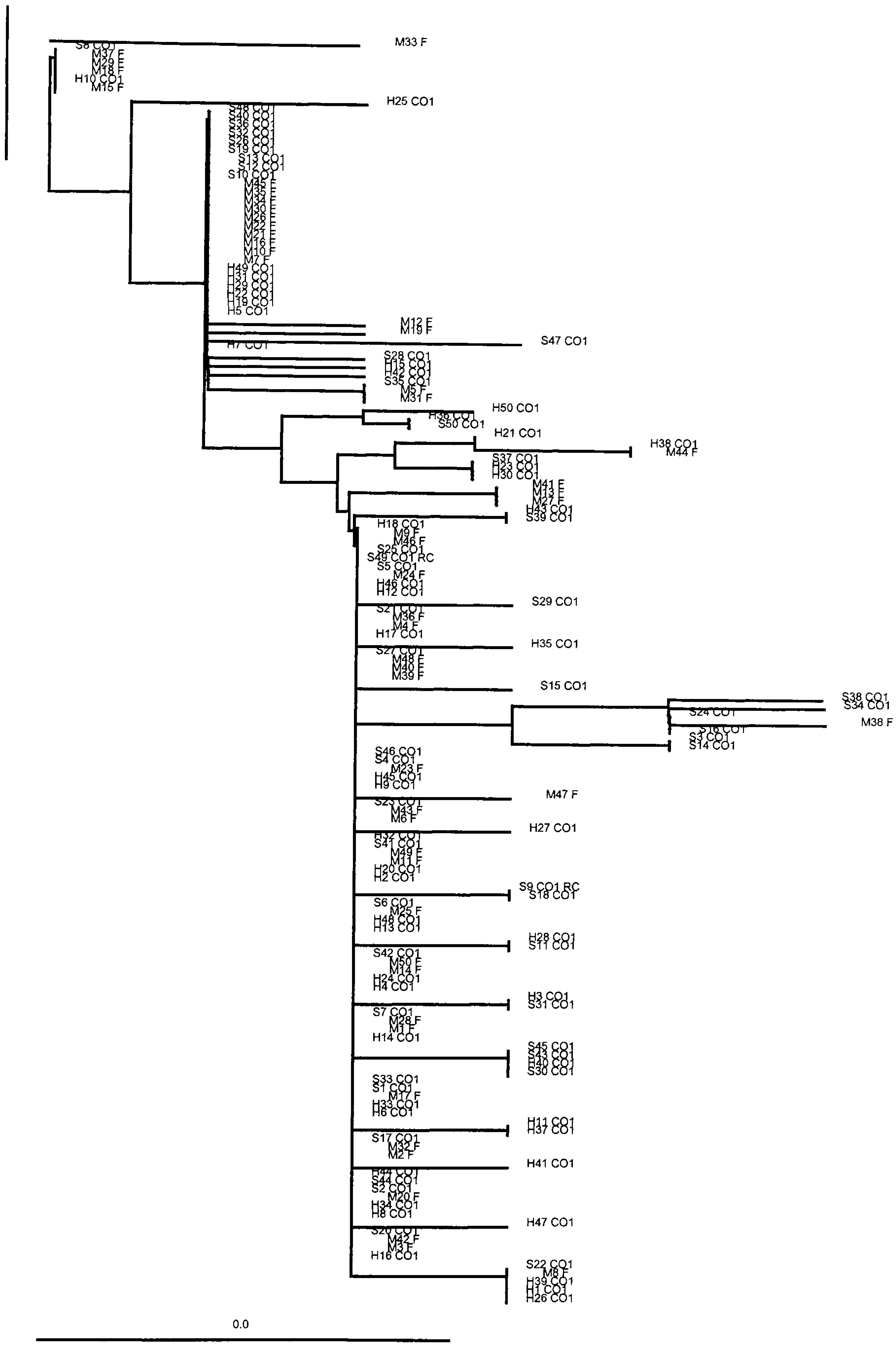


Figure 5.7 Dendrogram showing Phylogenetic relationship of all the 150 specimens sequenced in the CO1 region.

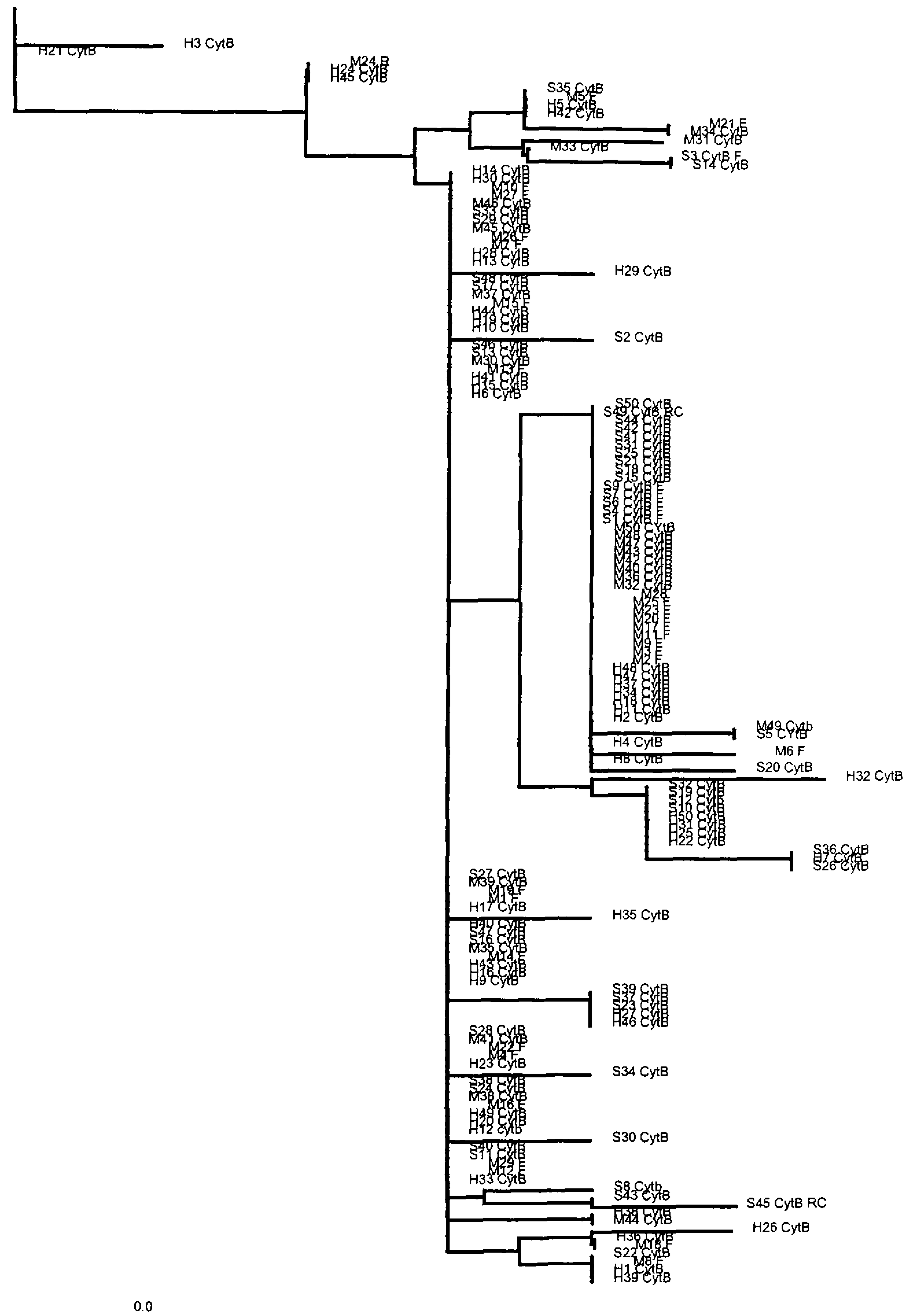


Figure 5.8 Dendrogram showing Phylogenetic relationship of all the 150 specimens sequenced in the Cyt B region.

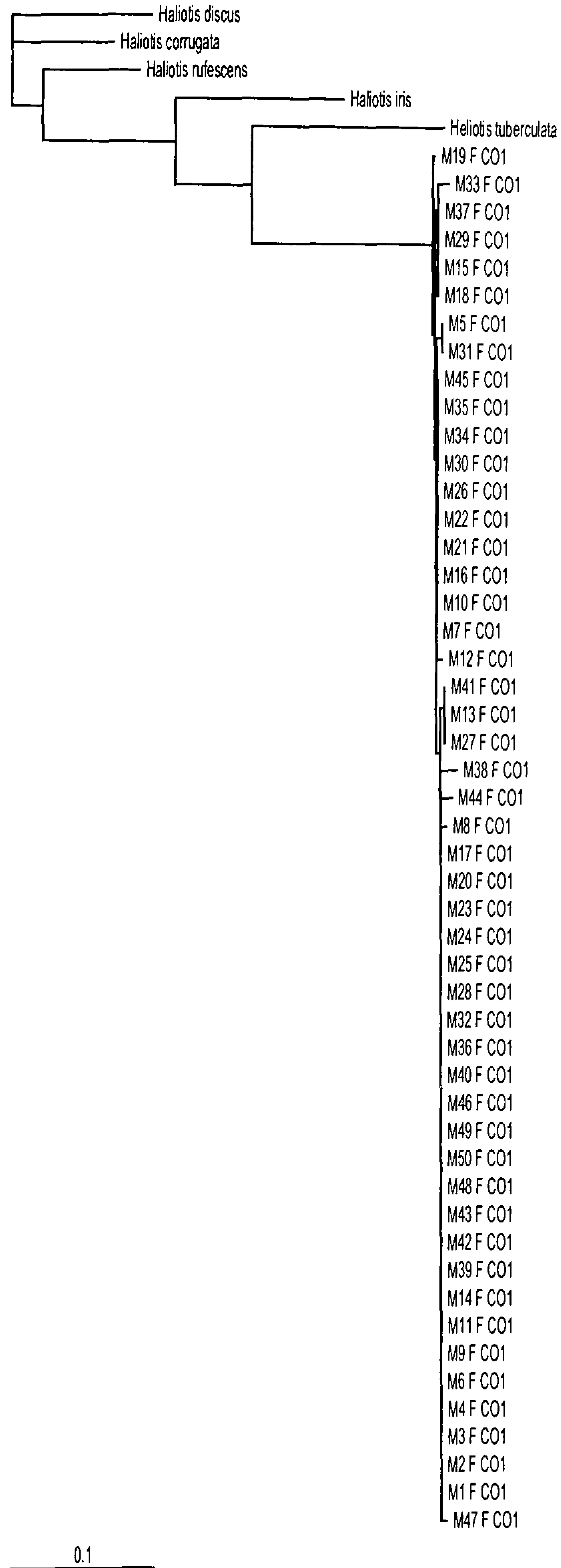


Figure 5.9 Comparison of all the 50 Abalone samples collected from the Mirbat area with the 5 known published samples from all over the world.

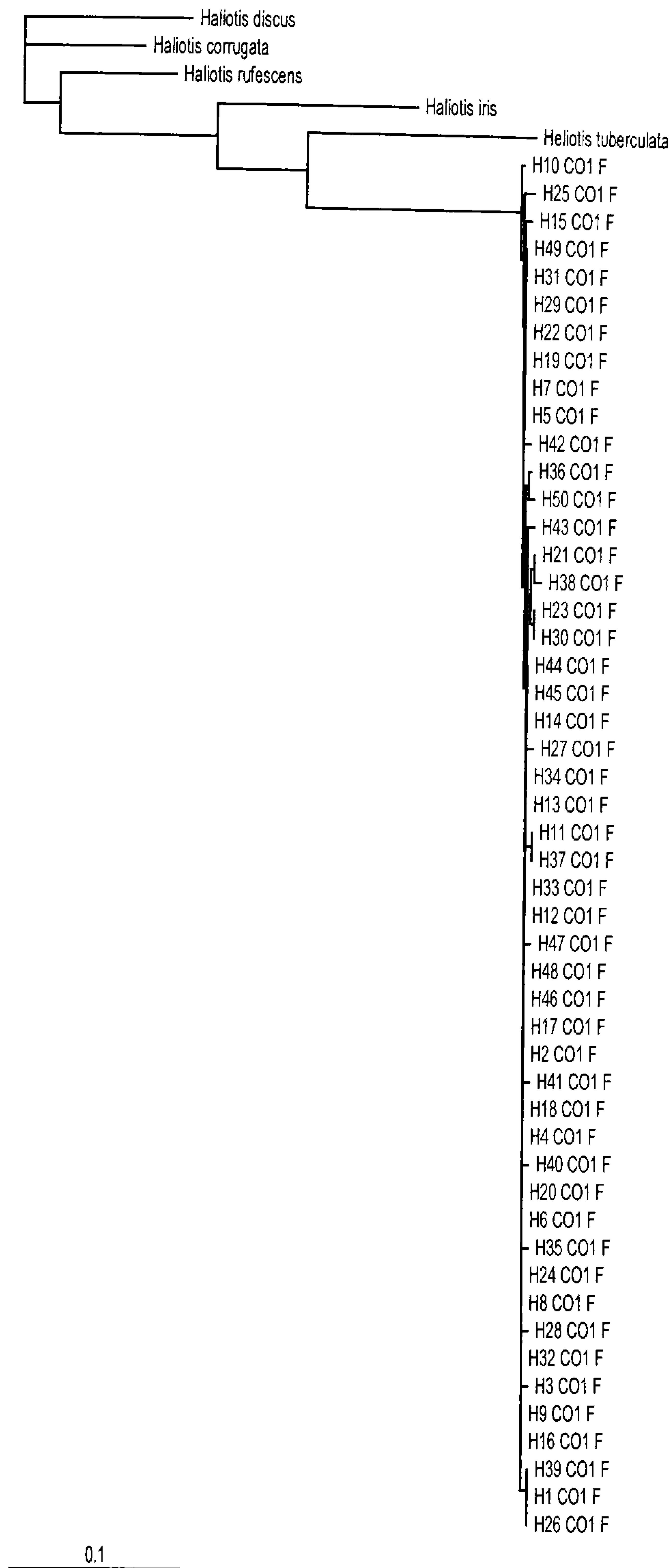


Figure 5.10 Comparison of all the 50 Abalone samples collected from the Hadbin area with the 5 known published samples from all over the world.

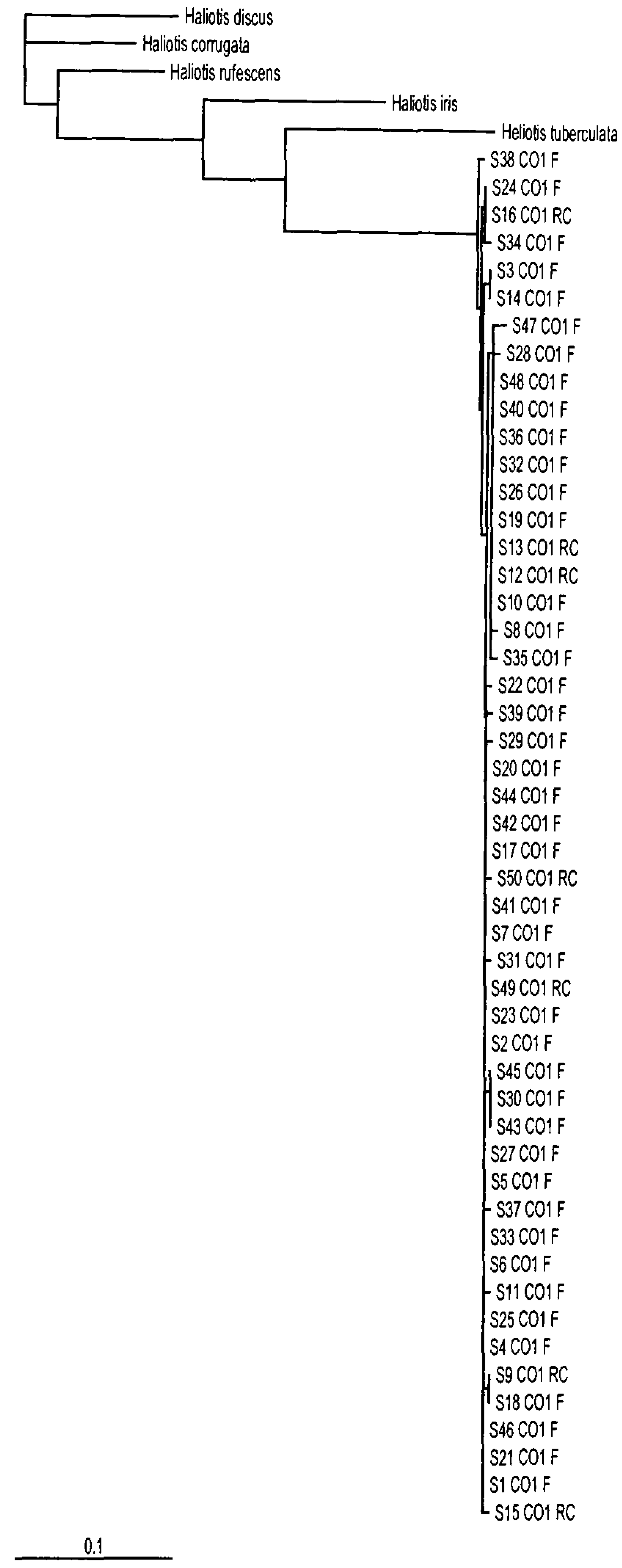


Figure 5.11 Comparison of all the 50 Abalone samples collected from the Sharbithat area with the 5 known published samples from all over the world.

CHAPTER 6
MANAGEMENT

6.1 Fisheries Management and Sustainability

6.1.1 Introduction

Fisheries resource management has become an issue since concerns about over-exploitation or resource competition have been raised in capture fisheries, which account for the bulk of the world's aquatic animal harvest (Thorpe *et al.*, 1995). The main objective of fisheries management has been, for some considerable time, the conservation of exploited fish stocks (King, 1995), although social and economic objectives are also important. Management practices generally focus around setting and observing input and output controls, such as catch, individual size, fishing gears, fishing areas, and seasons. The intention is to limit or prevent the harvest of smaller and less mature individuals to ensure sufficient breeding stock remains to maintain the stocks, and to conserve the habitat and ecosystem.

However, fisheries management world-wide has failed to protect and conserve many marine resources. Therefore, the need to adopt an integrated approach to management of marine resources has been recognized (Gulland, 1974; FAO, 1997). This approach to management is being seen as the only way forward in the future of aquatic resource management (Joseph, 2000). A working definition of the integrated approach has been proposed by the Food and Agriculture Organization (FAO, 1997):

"The integrated process of information gathering, analysis, planning consultation, decision making, allocation of resources and formulation and implementation, with enforcement as necessary, of regulation and rules which govern fisheries activities in order to ensure the continued productivity of the resources and accomplishment of fisheries objectives"

The FAO (1997) further expanded on the definition of management by detailing what should be entailed based on the above definition. These include the following:

- Setting policies and objectives for each fishery or stock to be managed, taking into account the biological characteristics of the stock, the nature of the existing or potential fisheries and other activities related to or impacting on the stock and the potential economics and social contribution of the fisheries to national or local needs and goals.

- Determining and implementing actions necessary to enable management authorities, fishers, and other interest groups to work towards the identified objectives. This task should be done in consultation with all other interest groups. The actions required will include developing and managing stocks; ensuring that the stock or stocks and the ecosystems in which they occur and their environment are maintained in a productive state; collecting and analyzing biological and fisheries data necessary for assessment, monitoring, control and surveillance; adoption and promulgation of appropriate and effective laws and regulations necessary to achieve the objectives and ensuring that fisheries comply with them to achieve their objectives.
- Consultation and negotiation with users or interest groups concerned with the resources and from areas not directly related to, fishing activities but which impact on the fisheries. The management authority needs to ensure that the interest of fisheries are appropriately considered and catered for in the planning and integration of activities.
- In consultation with users, regularly revising the management objectives and measures to ensure that they are still appropriate and effective.

It is clear from the above statement, that management of any marine resources is a dynamic and information-intensive undertaking to be effective and relevant to the current biological, economic, social, political and cultural environment. Cushing (1979) simply expressed the fundamental aim of fisheries management as the prevention of disaster to secure the resources for future exploitation. However, further expansion on this idea by Hilborn & Walter (1992) stated that the principal aim of fisheries management is to ensure the sustainable production over time from fish stocks, preferably through regulatory actions that promote the economic and social well-being of the fishermen and the industries that use the production. The Brundtland report (1987) identified sustainability as meeting the needs of the present without jeopardizing the ability of future generations to meet theirs.

6.1.2 Responsible Fisheries

In order to manage fisheries on a sustainable basis, the FAO proposed a Code of Conduct for Responsible Fisheries (FAO, 1995). The Code consists of a collection of principles, goals and elements for action, which have been elaborated by many different groups and experts involved in fisheries and aquaculture. The Code represents a global consensus or agreement on a wide range of fisheries and aquaculture issues. It is designed to help conserve and manage the world's fisheries, and aims to maintain or restore fish stocks to levels capable of producing reasonable amounts of catch for both present and future generations. Fishing operations and policies should be designed with a view to achieving long-term sustainable use of fish resources, as a means of assuring resource conservation and continued food supplies, as well as alleviating poverty in fishing communities. Therefore, the purpose of the Code of Conduct is to help countries and groups of countries to develop or improve their fisheries and aquaculture to reach this goal.

With regards to Fisheries Management the Code of Conduct for Responsible Fisheries (FAO, 1995) includes the following tasks:

- Countries should have clear and well-organized fishing policies in order to manage their fisheries. These policies should be developed with the cooperation of all groups that have an interest in fisheries.
- In fishery resources shared among regions, local fishery organizations should be established or existing organizations strengthened. Cooperation in this way is the only realistic approach to achieving the long-term goals of maintaining and conserving stocks to be sustainable.
- It is important to develop and implement a clear fisheries management and legal framework, so that all groups involved in fisheries have a clear understanding for rules to be followed.
- Fisheries should be managed to ensure that fishing activities are conducted in ways that do not harm stocks and reduce and minimize negative impacts on the environment.
- Governments should have enforceable laws with procedures for determining and punishing violators. Punishment for violations could include fines or even the removal of fishing licences if violations are severe.

- When developing fisheries policies, it is important to consider a number of issues. These include, among other things, the costs and benefits of fishing and the environmental and social impacts of fishing.
- The best scientific information available should be used when preparing the policies, while taking into account traditional fishing practices and knowledge where it is appropriate to do so. In the absence of adequate scientific information, countries should act more cautiously in setting fishing limits.
- All groups and organizations concerned with fishing should be encouraged to share views and opinions on fishing issues. Particular attention should be given to the needs of local people who depend upon fisheries for their livelihoods. Countries should strive to educate and train fishers and fish farmers, so that they can be involved in developing and implementing policies to ensure sustainable fisheries now and in the future.
- In order to protect fish resources, dynamiting, poisoning and other destructive fishing practices should be prohibited in all countries.
- Countries should ensure that only fishing vessels permitted fish in their waters. Such fishing should be done in a responsible manner and in accordance with any rules, regulations or laws that may be applied by a country.
- To avoid over-fishing, fishing operation and levels as well as fishing gears and methods should be identified and controlled and their impact should be well understood in order to reduce any impacts on stocks and environment.
- To protect fish resources, any destructive fishing gears and practices should be prohibited in all countries.
- Important fish habitats such as wetlands, mangroves, reefs and lagoons should be protected from destruction and pollution. Where natural disasters harm fisheries resources, countries should be prepared to take emergency conservation and management measures when necessary.
- To avoid disputes and conflict between different users of resources, countries should have policies and plans to ensure that resources are used and allocated on a fair basis.
- Countries should take steps to ensure that the livelihood of local communities, including access to, and productivity of, fishing grounds are not

negatively affected by aquaculture developments. Procedures for monitoring and assessing the environmental effects of aquaculture should be established. In addition, care should be taken to monitor the types of feed and fertilizer used in farming fish. The use of disease-control drugs and chemicals should be minimal because these can have important negative impacts on the environment. It is also important to ensure the safety and quality of aquaculture products.

- Before introducing non-native species of fish for farming, countries should consult with neighbouring countries if the effects of fish farming may extend beyond the country's waters.
- To minimize disease from new species, countries need to establish mutually agreed codes of practice or behaviour for introducing and transferring aquatic plants and animals from one place to another.
- Techniques should be developed by countries and industry for restoring and increasing the supply of endangered species, when planning aquaculture projects.
- When deciding how coastal resources (for example, water, land) should be used or accessed, the people, including fishers, who live in the area, and their ways of living, should be considered, and their opinions taken into account in the planning process.
- Where the coastal zone has multiple uses, fisheries practices should be carried out to avoid conflict among fishers and other users or, if disputes do occur, ensure that they are settled according to established and fair procedures.
- Countries with neighbouring coastal areas should cooperate with one another to ensure that coastal resources are conserved and well managed.
- Countries should recognize that responsible fisheries policy requires a sound scientific basis. Therefore, countries should make research facilities available and encourage training of young technicians.
- Countries should monitor the conditions of fish and their habitats and watch for any changes occurring in these conditions.
- Data should be gathered on the effects of different types of fishing gears on target fish populations and on the general environment.

- Countries should join together in international research efforts. Where research is undertaken in another country's waters, it is important that researchers abide by the fishing regulations put in place by the host countries. Fishing and supporting scientific information should be provided to regional fishery organizations and distributed to all interested countries as quickly as possible.
- Cooperation in matters relating to fisheries should reduce the likelihood of fisheries disputes. If disputes do arise, effort should be made to settle them as quickly as possible and in a peaceful manner.

If comprehensive and integrated policies, as recommended in the Code of Conduct for Responsible Fisheries (FAO, 1995), are implemented in the fisheries sector, and responsible fishing and utilization practices are followed, this will result in a healthy, more robust sector. In the longrun, with such a responsible approach, the natural resources will remain productive and sustainable. Moreover, responsible aquaculture and fish farming makes important social and economic contributions to farming communities and the economies of their counties.

6.1.3 General management of abalone fisheries

The main objective of abalone fisheries management worldwide has been the conservation of abalone stocks and exploitation on a sustainable basis. Unfortunately, over the past four decades, many stocks of abalone have been overexploited, almost to the point of extinction. These activities pose a severe threat to the world's abalone fisheries resource. All natural populations of abalone are affected by a variety of commercial and environmental pressures. It is not surprising, therefore, that interest in managing abalone fisheries or individual stocks has grown. Shepherd & Johnson (1991) stated that for effective abalone management it is important to clarify the goals. A fundamental goal is optimum sustainable yield, which has three key elements:

- maintaining a biomass, which provides a large reproductive capacity;
- producing high quality abalone by using rapid pre-reproduction growth to an optimal size;
- providing maximum economic benefits to society.

There are other goals, such as biological goals to maintain the ecosystem stability, social goals to minimise unemployment and economic goals to increase export quantity (through regulating size of capture) and to reduce the costs of management.

The same authors indicate that many types of measures have been used in abalone fisheries to achieve good management. Licence limitation and harvest closures, either area or season, have been used as input controls. Quotas, size limits and export controls have been used as output controls. All these measures have advantages and disadvantages. For example closed areas or seasons can be effective, but area closures can be disadvantageous because removing fishing effort from one place may concentrate it in another. Permanently closed refuge areas can be advantageous. They can maintain genetic diversity and preserve remnant stock if over-fishing has occurred, increase egg production substantially, and provide a place for long term studies. Size limits, which are considered to be an enforceable and effective method of control, can, where growth rates vary widely, over-protect slow growing components of a population and under-protect fast growing components. It is difficult or impossible to achieve optimal management in a single measure, but a proper enforcement of a large size limit with appropriate seasonal restrictions can help to obtain good management.

Globally, the entire range and combination of management options have been used to manage abalone fisheries with varying levels of success. The management of the Tasmanian abalone fisheries has been recognized as the most important example to date of a properly managed fishery. The fishery is controlled by input measures, size limits, and licence limitation, and by output measures and individual quota (Prince & Shepherd, 1992; Shepherd & Rodda, 2001). Similar management options have been adopted for management of the Omani abalone. They include mainly conservation measures such as: minimum harvesting size (90 mm SL); closed seasons; gear restriction; minimum diving depth 8 metres; and fishing rights (Al-Hafidh, 1999). These are detailed in the next section, on management of the fisheries sector of Oman.

6.2 Management of Fisheries Sector of Oman

6.2.1 Government Strategy

The main goals of the Government of Oman towards fisheries include:

- The best utilization of aquatic resources that can be achieved through maintenance and development of the fisheries, management of coastal areas, fisheries research and extension to realize the concept of rational fishing;
- Diversification of national income by raising the contribution from fisheries, realization of increasing development rates, development of fisheries exports and fisheries industries, technology transfer and development of infrastructure;
- Enhancement of well-being of fishermen and encouragement of their settlement through provision of necessary infrastructure and services, construction of model fishing villages, improved work environment in the private sector, supporting the economic role of women in rural areas and encouraging cooperative work in Omani villages;
- Raising the contribution of fisheries in food security and food quality. This can be achieved through raising the average per capita consumption of fish, improving fish distribution throughout the country and realizing remunerative income from fish exports in order to import other items not produced locally;
- Enhancement of the private sector's role in fisheries development and expanding its activities, through encouragement of private sector involvement in completion of infrastructure, and provision of technical and financial support to companies in the private sector in order to qualify them for export;
- Completing the construction of infrastructure.

In addition, there is no tax imposed on the fisheries sector, but there are certain nominal fees to be paid by the artisanal fishermen against the issue and renewal of fishing licences and boat registration, and the industrial sector is required to pay 12% of the value of the actual catch within the permitted quota (Ministry of Agriculture and Fisheries, 1994).

6.2.2 Fisheries Policy and Objectives

The policy of the government towards the fisheries sector clearly focuses on development of the fishing industry and ensuring its sustainability for coming generations by promoting self-sufficiency through increased production of both marine and aquaculture species. The overall and specific objectives for the fisheries sector specified by the Ministry of Agriculture and Fisheries (1994) include:

Overall fisheries management objectives:

- Development and modernization of the fisheries sector;
- Development of fisheries exports;
- Enhancement of economic diversification of the country through fisheries development;
- Development of aquaculture projects;
- Enhancement of the future production and value of Oman's coastal fisheries and the well being of the people and coastal communities.

Specific fisheries management objectives include:

- Reserving marine resources within the Exclusive Economic Zone (EEZ) for the benefit of the country;
- Ensuring effective enforcement of the existing fishing law and regulations;
- Protecting and maintaining living aquatic resources;
- Protecting the fragile coral reef and other inshore environments;
- Using traditional knowledge and interests of artisanal fishermen and communities in fisheries management;
- Promoting fisheries scientific research ;
- Ensuring integrated planning and a collaborative approach in terms of policies for the sector, fisheries and coastal zone management;
- Cooperating with neighbouring countries in management of shared and migratory stocks.

6.2.3 Management Systems of Fisheries Sector

To help ensure future sustainability of Oman,s marian resources, the fisheries sector is governed and organized by the Marine Fishing and Living Aquatic Resources Law, issued by the Royal Decree Number 53/81, and the Executive Regulations of the Law, issued in accordance with the Ministerial Decisions Numbers 3/82, 4/94, 121/98, and 136/98. The Executive Regulations deal with Marine Fishing Licences, Licence Fees, Protection and Development of the Living Aquatic Resources, Regulation of Fishing, Preservation, Transport and Marketing of Living Aquatic Resources, Quality Control of Exported Fish, conditions and specifications of Industrial Fishing Vessels Equipped For Preservation and Handling of Fish Products, General Provisions and Penalties. These rules and regulations are intended to protect and conserve the fisheries and marine resources through controlling the way of exploitation these resources.

The types of fisheries in Oman include demersal fisheries, large pelagic fisheries, small pelagic fisheries, shellfish and mollusc fisheries including lobster, shrimp, abalone, cuttlefish, shark and ray, and other species such as sea cucumber. Both traditional and industrial fisheries, and the fisheries resources, are managed on a fishery-specific/species-specific basis. In each management system, several control measures are directed towards the conservation and development of the fishery.

Management of the abalone fisheries, until recently, has been undertaken with a top down approach. The control measures that must be adhered to include:

- **Restricted Fishing Season:** A harvest closure season was introduced for the first time in 1987 with an annual closed season of six months, from 1 April to 1 October. Prior to that, the harvest had been open all year round, depending on weather and sea conditions. In recognition of over-fishing problems and the decline of the stock, the fishing season was reduced in 1991 to be only two months (November and December). In 1999, due to the occurrence of the fasting month, Ramadan, within this period and as a response to divers' request, the fishing season was put back from 15 October to 15 December. A few years later, the fishing season was changed to be after Ramadan and last for a period of two months each year, which is still the same today.
- **Size Limit:** A minimum legal size limit of 90 mm shell length was introduced in 1991 and it is still the same today. Diving for and collecting as well as handling of abalone of less than 90 mm SL is strictly forbidden.
- **Diving Depth Restriction:** Diving for and collecting abalone is not allowed in shallow waters of depth less than eight metres.

- **Diving Gear Restriction:** Using any artificial breathing diving gears such as SCUBA or Hookah (compressed air) is prohibited; only skin diving is allowed.
- **Transaction Restriction:** Handling and possession of abalone outside the fishing season, including its transportation, trading and export, is against the law.
- **Export Permission:** An export certificate must be obtained from the Department of Fisheries to export abalone.
- **Surplus Record:** Abalone traders, divers, or companies with surplus abalone at the end of the season are required to register their quantities with the Department of Fisheries. Any dealings thereof should only contain those registered quantities, and required authorities' permission.
- **Fishing Right:** This employment is restricted and can only be practiced by Omani fishermen of the southern region.

Breaking these regulations may attract penalties including:

- Fines of 300 O.R. (US$ 777) and up to 5000 O.R. (US$ 12953) and/or
- Jailing for one month or up to three months and;
- Confiscation of the catch and the equipments and gears used in the crime and;
- Cancellation of fishing licence.

These penalties are doubled for a second offence (Ministry of Agriculture and Fisheries, 1994).

These management options focus mainly on sustainable production by implementing measures to reduce fishing effort, which include input control, output control and conservation measures. Conservation measures such as closed season, minimum landing sizes, restriction on gears, depths and methods, and fishing utilization rights have been used to control the abalone fishery and to attain management goals. Unfortunately, these measures are not strictly enforced, and in the majority of circumstances are based on inadequate knowledge of the fishery or stock.

Since 2003 there has been an attempt by some active fisheries managers at the southern region Fisheries Department to introduce new measures such as a Diving Licence System and a Size Monitoring System for traders who purchase abalone, but these failed to be applied because they were rejected by the resource users. This was because of the introduction of such measures will restrict divers' landings of small sizes and will collide with their business, also because they were not based on enough scientific evidence and because of deficiencies in administrative procedures. The use of appropriate measures with strong enforcement, backed up by a programme to monitor stocks and fishing practices, is thus needed to ensure the future status of the abalone fishery in Oman.

6.2.4 Constraints in the Regulations and their Implementation

Institutional and legal limitations

The designated rules and regulations seem to be suitable to protect and conserve the abalone resource if they are strictly implemented and enforced. Although these measures have been used for more than fifteen years, their enforcement has been insufficient. According to Shepherd & Johnson (1991), at the beginning of the 1991 fishing season, 50% of the divers catch at some sites was undersized, and at the end of the season it was as high as 90%. In addition, many divers are from other regions and fishers are diving out of the season.

Despite the existence of the Surveillance Department to monitor, control and supervise the fisheries and to provide back up and support to the Fisheries Departments in all regions of the country, these regulations are ignored by different user groups. The minimum legal size in place (90 mm SL) is not respected by divers, and more than 50% of their catch is below this limit. These under-sized abalone are also accepted by traders. The restricted diving depth is ignored, and more than 90% of the diving operations take place in depths less than 8 metres. Moreover, many divers dive out of season and their catch finds its way to the export market through the traders. All these violations are due to lack of surveillance and ineffective enforcement of penalties. There is no efficient system of monitoring and controlling the resource. The surveillance days are normally very limited due to the limited number of officers, and lack of vehicles, facilities and funds. The short surveillance visits normally take place during the fishing season and sometimes according to a command from the higher authority as a response to complaints from the public. When officers enforce the rules and fine and apprehend illegal divers or traders, the latter might be released and a higher authority as a conciliatory gesture often cancels their fines. In such a situation, the officers become unwilling to fine or apprehend any divers. With no strict enforcement of fines and penalties to prevent and deter the lawbreakers, other diver groups are encouraged to ignore and break the law.

Insufficient scientific background

Most of the regulations in the Abalone Fisheries Act were formulated a long time ago, and/or based on very limited scientific information. For example, the fishing season was recommended and introduced in 1987 to conserve the depleted stock, and has been revised several times. However, the results of this study suggest that most of the animals during the current fishing season are fully mature. This is in accordance with previous studies (Sanders, 1982; Savidge *et al.*, 1986; 1988; Siddeek & Johnson, 1993; Ogawa, 1994; 1997; Stirn & Al-Hashmi, 1996; Al-Hafidh, 1999; Iwao 2000). Thus, the current fishing season is incorrect with respect to maturation and should be changed based on recent findings.

There is also a general lack of consistent time series fisheries data, which are essential for making rational management decisions and assessments of the achievement of the implemented management measures. Statistical data for the early years are either unreliable or missing, compared with more recent years. It is this lack of basic information on the fishery and stock status needed for management that makes managers reluctant to implement and enforce the regulations.

Topographic complications and lack in surveillance capacity and facilities

Unfortunately, the coastline where the abalone fisheries operate is long and characterized by difficult and varied topography. The majority of fishing grounds are located in remote areas served by poor roads. Monitoring the fishery in these areas would require large numbers of fisheries personnel and facilities, which are not available. This is because it is beyond the capacity of the Department of Fisheries in the southern region to provide the funds needed for surveillance activities. Therefore, it is very difficult in these circumstances for a limited number of observers, with very few cars and boats, to reach or cover the vast fishing grounds. Thus, they always concentrate their surveillance in areas close to and around the traders' camps. However, while these inspectors are far away, many divers are breaking the law by collecting small sizes in the sheltered lagoons, turning over the boulders and diving off season. The bureaucratic nature of management administration in different Fisheries Departments also impedes effective enforcement of these regulations.

Sense of ownership

The abalone fisheries are restricted to a specific coastline in the southern region of Oman, which, according to the law and the classification of fishing zones, can only be exploited by the fishers from this region. As mentioned previously, due to the lack of surveillance and because of the high value of abalone, this fishery attracts many fishermen from other regions who ignore the regulations and move to this region during the fishing season to participate in the diving activities. The local divers believe themselves to be the owners of the resource, and view the foreign divers as competing with them to exploit their valuable resource. For that reason, and in the absence of law enforcement to protect their resource, local divers tend to exploit and harvest the resource a few weeks before the fishing season started and before the outsiders arrive. The issue of sustainability of the resource only arises if all the resource user groups are concerned. Thus, failure to have strict enforcement in applying the right of utilization of the resource is a serious deficiency in the implementation of the regulations.

6.2.5 Barriers to Managing Abalone Resources

Several factors limit and complicate effective management and conservation of the abalone resources in Oman, ranging from a lack of scientific information and knowledge or technology to the need for effective and strict law enforcement, sufficient and appropriate surveillance and monitoring programmes, attention of both the management authorities and resource users to the serious situation of the stock and the magnitude of this fishery.

Lack of information: Little is known about the different aspects of this fishery. Due to lack of scientific research in the fisheries field in this region and because abalone is a small fishery restricted to relatively remote and inaccessible areas, research has been given little attention since collecting data on this fishery is relatively difficult, and only a few studies are available. With the exception of this study, no genetic investigations have been done on this species. Despite 35 years of exploitation of this resource, scientific research on abalone has not received adequate priority or funding, and a comprehensive study on the stock status of *Haliotis mariae* and fishery related aspects does not exist. Making conservation and management decisions in the absence of scientific information may inadvertently place the abalone resource at risk. The available knowledge for managing abalone resource is inadequate. Although some information is available for *Haliotis mariae*, more studies and detailed information are required on different aspects of the fishery. Research is required to develop a practical management plan to conserve the abalone resource. Although activities related to abalone aquaculture and stock enhancement have been carried out for over 10 years, lack of information, limited funds and complicated administrative procedures are barriers to development.

Lack of effective enforcement of the law: The institution responsible for managing and conserving abalone resources is the Ministry of Agriculture and Fisheries. In many cases, those with the responsibility to manage abalone resources and to regulate divers' activities have failed to apply effective strict penalties against the law breakers, which encouraged them to continue breaking the law, and ignore all the regulations and rules concerned with the protection of this resource. In addition, when the inspectors capture or fine the abalone poachers and law breakers, these fines might later be cancelled by a higher authority, due to preserve social relations.

Lack of observers and conservation focus: Despite the importance of this fishery and that it has been intensively fished for a considerable time, the protection and conservation of the fishery have not been given high priority or received adequate protection. Relatively few inspectors are assigned to the surveillance and protection of the fishery, and they are provided with only very limited facilities. In addition, diving training programmes for abalone inspectors are not provided, making it impossible to control fishing activities. It is necessary to draw the attention of the Ministry of Agriculture and Fisheries to the urgent need to assign more fully equipped inspectors and to give them more authority, comparable to those of the Nature Conservation of the Ministry of Environment.

Lack of job opportunities: Most of the families living along the coastline between Mirbat and Sharbithat are dependant on this fishery as a source of income. The lack of opportunity to get a job or find other sources of income, coupled with the high income that can generated from this source, makes this fishery vulnerable to heavy fishing, without consideration to the serious status of the stock.

Lack of cooperation and communication between management authority and the resource user groups: Typically, management and conservation programmes are developed, implemented, and enforced at the regional and local levels. The effectiveness of the management often depends on resource users' cooperation and respect for the law. Abalone user groups are not invited by the management authority to participate or to present their opinions regarding the resource or when decisions are made, which may result in these decisions being ignored. A cooperative action plan should be established between the Ministry of Agriculture and Fisheries and all the resource user groups to develop and implement appropriate policies for successful management and conservation of the stock.

Lack of awareness programme: While public concern exists in Oman for some charismatic wild species such as Oryx and aquatic species, such as turtle, the case for conserving abalone should be known and respected by the public. There should be greater public awareness of the importance of abalone resource, the serious status of the stock and the need for conservation. Awareness programmes through the media and press campaigns will help in attract public concern about this species.

Lack of education: The implementation of effective policies to conserve any resource requires some level of knowledge and educational background. However, most of the abalone divers have low levels of education and do not recognise the effect of their wrong practices by catching the small sizes and turning over the boulders, and the impact of such practices on the sustainability of the fishery. Professional education and training programmes must be introduced to the local communities to enable divers to understand the importance of the marine resources and how they can help in the conservation and protection process.

The current management programmes fail to conserve abalone resources. Major radical policy and management actions, more research, education, awareness, cooperation and monitoring efforts will need to be enacted and enforced to prevent stock deterioration and extinction and to ensure the conservation of the abalone resource.

6.2.6 Abalone Threats (Key Issues)

Generally, abalone is vulnerable to over-exploitation because this species has a short larval period, is slow growing, relatively long-lived (and therefore matures slowly), sedentary and has low or sporadic recruitment (Shepherd & Johnson, 1991). Moreover, abalone occurs in the coastal water, and mature individuals tend to aggregate and accumulate in patches in the shallow water, where they become easily accessible to divers.

For the Omani abalone *Haliotis mariae*, there are many limiting factors. Although some measures have been introduced to control and protect this resource, many problems have begun to appear, which have started to threaten the resource, so that the fishery has undergone a marked decline. Some of these problems are a result of wrong practices by the divers themselves and their failure to observe the relevant controls, a problem exacerbated by ineffective enforcement and/or inadequate penalties for the law breakers. Other problems are due to environmental changes or because of forces of nature, such as competition and predators.

Breaking the rules and poaching of abalone continues to be a major problem. Without effective law enforcement, illegal harvesting not only depletes already depressed abalone stocks, but also reduces their reproductive potential, by removal of mature and ready to spawn abalone. Moreover, the results of the survey undertaken in this study showed low density *Haliotis mariae* population, and mature individuals of both sexes are separated. This reduces the chance of fertilization and so lowers the number of recruits.

Enforcement of the rules is difficult, but without reductions in illegal harvest, protection of enough brood stock, a continued monitoring of the fishery, and other effective rehabilitation methods, abalone population abundance will likely remain low or more likely continue to decline in most areas of the southern coast of Oman.

Some of these problems are beyond the scope of this study. Therefore, the key issues presented below are only those, which are relevant to the observations and findings of this study.

Over-exploitation of the fisheries resources

Abalone is a highly prized sea food, the price of which is continually increasing. This, coupled with abalone occurring in shallow accessible water, attracts many people to engage in the diving activities. As a result, the number of divers has increased rapidly from 1467 divers in 1988 to over 2049 divers in 2003. The intensity of divers' fishing effort has increased dramatically in recent years due to competition from divers from different regions exploiting the same, already depleted, stocks. The situation was totally different when the price was low in the early days of the fishery and abalone was abundant, and when there were only a few divers. The current number of divers is way above what the stock can support. The recent intensive survey conducted along the coastline from 23 March to 25 April 2005 (Chapter Three) found a very low density of the stock in all fishing grounds. Catch per diver has fallen despite increases in number of diving hours, improvement in diving capabilities using fins, snorkel, diving torches and wet suits, collecting of small sizes and change in diving practices by turning over boulders in search of abalone. This is largely the result of unavailability of abalone and inappropriate mechanisms to controll divers' entry into the fisheries.

Abalone usually inhabits easily accessible inshore waters, offering easy reach and exploitation of this resource, Therefore, the abalone fishery is very attractive to different groups. As a result, pressure on small immature abalone has become intense, especially in the last few years. These small sizes can usually be found under the boulders and rocks in the inshore shallow water areas. The collection of these small juveniles < 70 mm SL by shore-pickers, such as women, young and elderly non-swimmer divers, is encouraged by the high market price and the absence of law enforcement, together with the encouragement of traders who accept these small sizes. Similar pressure is imposed on small sizes by professional divers in deeper waters, where large sizes are mostly over-fished. Moreover, some divers collect small sized individuals as gifts when returning home after the end of the fishing season. Samples from abalone divers' landings during the 2003 fishing season showed that about 50% or more of the divers' harvest was below the minimum legal size of 90 mm SL. An attempt to introduce a monitoring system applied to the traders' daily abalone purchases was made in 2004 and again in 2005 by the Ministry of Agriculture and Fisheries to reduce the purchase of small sizes, but this was rejected by the traders and then stopped by the Ministers' decision in response to a request from the traders. Consequently, most of the remaining stock is dominated by medium and small sizes, which may not support the fishery. This high intensity of small and immature abalone collection, together with the decline in the number of large mature breeders, will compromise the recruitment capacity of the stocks. Therefore, the fishery is currently experiencing serious over-fishing and is in danger of depleting the stock. With such a high level of illegal fishing of undersized specimens, no fishery can be sustained and this will ultimately lead to a collapse of the whole fishery.

This species is known to prefer a particular habitat, which appears to be related to the availability of crevices and cracks in the rocks and under the boulders. Usually the abalone seeks dark places, especially the under surfaces of these boulders and often attaches itself to them for protection from predators. At present, and with the lack of emergent and visible abalone, divers' fishing practices have changed and many divers today, when searching for abalone, turn over these boulders using various tools to move the big rocks, and leave them overturned on the bottom. The undersides of these boulders usually have a cover of encrusting pink Corallines which is the preferred habitat for settlement by larval abalone. This layer of Corallines, which also represents the main source of food, is bleached by light and killed and removed by the currents and water movement. Moreover, the larval and juvenile abalone living under these boulders become easy targets and are quickly eaten by fish and other predators (Johnson & Shepherd, 1992). These unwise practices destroy the abalone habitat and alter the natural environment. During the intensive survey of the abalone habitat, most of these habitats appeared to have been were destroyed. The situation is particularly worrying in the heavily exploited inshore shallow waters.

The divers usually use a steel device to dislodge and remove the abalone from the cracks and crevices in the rocks. There are no specific standards for these tools used by divers; each diver uses different self-designed dislodging tools, such as a modified large screwdriver. Removing the abalone frequently injures them. With the inadequate tools, the diver might fail to remove or collect the abalone from narrow crevices, and as the abalone have no clotting agent in their blood, these injured abalone bleed to death. As most of the current divers are inexperienced, the incidence of such practice is very high and consequently, sub-legal sized mortality has increased.

As has been mentioned previously, abalone fishing is permitted for only part of the year, from 15 October to 15 December. It is permitted along the coastline in accordance with the regulations controlling this fishery. Due to the high price of this species together with the absence or lack in observation and monitoring the coastline, many local divers ignore the regulation to protect abalone, and dive out of season year around, and particularly in the few weeks before the season starts. This is in a race to collect the abalone while it is still in greatest abundance and before other divers from other regions come and compete with them to collect it at the beginning of the season. These divers usually dive during the night but also the day time and gain access to the fishing ground through sheltered gullies in the remote areas, and in places away from the inspectors' reach. Ogawa (1997) reported that most of the abalone caught before the fishing season were fully mature and ready to spawn. As a result of diving out of season, the number of mature breeder abalone has decreased dramatically, affecting the rate of reproduction. This study confirmed the findings of Ogawa, as fresh abalone shells were frequently found in many popular diving sites at sheltered lagoons along the coastline. This was also supported by the frequent poaching events reported to the Fishery Department.

Open access to the fishery and ineffective nature of regulatory approaches to date

This fishery occurs in the inshore shallow waters in the southern region of the country. The fishery is open to all citizens of this region during the fishing season, and while some divers use boats in diving operations, most operate freely from points along the coastline. The diver is only required to have a general fishing licence and a registration certificate for the boat being used. These can easily be obtained by filling an application form and paying a small fee. Even these minimum criteria for entry are not necessarily adhered to. For example most of the divers operate without a fishing licence, and their boats are without registration numbers. In the absence of control, many fishers from other regions move to this region during the fishing season to participate in abalone diving activities. Therefore, the number of divers has increased rapidly and the resource is overexploited, leading to the declining of the stock.

This situation has been recognized for a long time, and during the 2004 and 2005 fishing seasons, attempts were made by some fisheries managers in the southern region to introduce a specific diving licence to control access to this fishery and to prevent exploitation of this fishery by outsiders, but that system was rejected by many divers and failed to be applied due to administrative obstacles. If honest attention by both the fisheries authority and the local resource users was paid to control access, the abalone stock might be better protected, but serious social and economic distortions commonly arise amongst the two parties. In this situation, this valuable and open access fishery attracts divers from different regions. Most of the divers operate from sunrise until sunset, and the local divers strive to collect as many abalone as they can, regardless of size, before their competitors from other regions. This race to dive leads to collection of small sizes, destruction of the habitat through turning over the boulders, fishing out of season and increased diver effort, most of which now feature in this fishery. Recently, to maintain a higher production in a situation where the number of entrants into the fishery is ever increasing, some divers have taken to diving at night. In many sheltered areas the divers use night torches and some divers are reported to use illegal breathing gears when diving.

To limit access to this fishery and reduce the threat, the current regulations in place should be strictly enforced, and the local divers should be involved in the monitoring and management process. Particular attention should be given to the indigenous people and local communities, who are dependent on abalone fishery for their income and livelihoods, when decision making. This will encourage a sense of ownership in the local community and increase their cooperation and responsibility to protect and conserve the resource. The local community might be encouraged to diversify their activities into other fisheries by providing them with necessary fishing gears and subsidies, or by establishing local fishery cooperatives or farming companies. This could reduce pressure on the abalone stock by creating new employment opportunities and guarantee local people a source of income.

High demand for abalone

Abalone is considered a delicacy by the Chinese and Japanese, and the popularity of this type of seafood has soared internationally, causing heavy fishing of many fisheries world-wide. Continuous overwhelming demand for these molluscs from the international market, which cannot be satisfied by the present supply, results in extraordinary prices for these products. During the last ten years, many fisheries around the world have been overexploited to the point of extinction or been closed, and the remaining fisheries seem to be under pressure (Gordon & Cook 2004). The abalone fisheries in Oman reflect this picture; this resource has been heavily exploited during the last few years, due to its high value. The abalone traders, to maximize their export quantity and increase their profit, provide the divers with credit or loans. In return, the divers must sell their harvest to that trader. Also, some traders employ some mobile collectors, scattered along the coastline, to buy the daily harvest of small divers and shore-pickers, which consists mostly of small sized individuals. However, there is always competition among the traders in offering attractive high prices to those divers to obtain their catch, regardless of size. These traders' practices encourage the divers to increase their effort, giving no attention to the regulations or stock status. Therefore, the high prices and obligated loans are probably the strongest forces behind the increases in diving effort in the abalone fishery despite declining catches. The traders somewhat contribute to the decline of abalone fishery in this country, either directly or indirectly by accepting these small sized abalone and through the strong competition among them in offering and increasing the prices paid to divers without any conditions or guidance from the Ministry. Moreover, in an effort to obtain greater quantities of abalone for export, most of the abalone traders are accepting any quantity of abalone regardless of the time of capture (season or off season) and within/or below the minimum legal size. Unless these practices are controlled, the effort of the divers will keep increasing to meet the traders' demand under the international demand. In addition, although abalone is very popular with most of the people in this region and in high demand, the internal market is less attractive due to the high prices of these products, which cannot be afforded, but it is still supplied with a considerable quantities of small sizes or sliced specimens rejected by traders, which are commonly given by divers to their families and friends each season, as valuable and appreciated gifts.

Factors related to environment and laws of nature

This fishery is strongly influenced by environmental changes, which control the availability of food sources restricted to the monsoon season. Moreover, the laws of nature act as another control factor influencing the availability of abalone; the competition effect of sea urchin resulting in the Isoyake phenomenon, and predators add another threat. The influence and effects of these factors have been discussed in more detail in Chapter 3.

6.2.7 Management Options

Although *Haliotis mariae* makes up only 0.03% of the production of the whole fisheries sector, it contributes about 6% of the total value of the sector income. Due to the nature of the present management system, the fishery of *Haliotis mariae* is largely unregulated, which could lead to the extinction of the already depleted stock of this important species of Oman

The Government's main objectives, mentioned previously, for the Management System of abalone stock were not successfully achieved. To meet these objectives, there is a need for a special management arrangement for the abalone fishery. As part of the Oman Abalone Management System, a minimum legal size limit was imposed on the diver landings, as well as a closed fishing season together with restrictions on fishing gears, diving depth and fishing rights. Unfortunately, these management measures were not enforced effectively. The minimum legal size is ignored by divers and most of their landings are below this limit. Moreover, more than 90% of the diving operations are taking place in the shallow waters at depths less than eight metres, and diving out of season and turning over the boulders are common practice among many divers. All these are as a result of lack of surveillance and weak enforcement of the law.

The results of the various studies presented in this thesis (summarized in Chapter 7) together with all the previous studies consulted and the field observations of the fishing grounds are all evidence of the serious situation of the fishery. Urgent and active action is needed to conserve whatever stocks remain, otherwise the collapse of this fishery undoubtedly will be imminent.

More control measures need to be applied and imposed on this fishery. As a matter of urgency and due to the present fishery circumstances, the existing regulations should be strongly and strictly enforced, and the Ministry of Agriculture and Fisheries should take special and urgent arrangements to provide the necessary requirements to apply the law and protect and conserve this resource. Unless illegal size landings are controlled as well as regulations and law enforced, the new conservations measures will do little to halt the decline of the over-fished stock.

Due to the complexity of social dependencies which the fishery has created and continues to create, co-management is seen to be the best tool and the only way to conserve and protect this resource. Abalone divers and traders, fisheries authorities, fisheries researchers, will have to cooperate and to take an active part in the process of choosing measures which are adequate to prevent over-exploitation.. Management options for the sustainability of this fishery are proposed below:

Option One: Total closure of the fishery

It is a difficult decision to close the fishery, but it may be necessary to save this resource from extinction. Johnson & Shepherd (1992) suggested a complete closure of the fishery or at least to increase the MLS to 110 mm to save the breeding stock. No attention has been given to their recommendation and none of these actions was considered by the Ministry, which has resulted in the recent status of the stock. Currently, increasing the MLS is not considered adequate as abalone abundance has already reached a critical level and most of the remaining stock consists of small and medium sizes. In addition, the old MLS of 90 mm was reasonable; but the problem was that it was not respected by divers due to weak enforcement of the law; a problem that might continue with the introduction of any new MLS. Both suggestions are certain to cause greatest hardship to divers, but temporary hardship is better than a complete collapse of the fishery and total loss of related income, not only for the current divers, but also for coming generations. Many wise divers recognize the current serious situation of the fishery and have frequently requested closure of the fishery for one or two years. Based on this study, together with previous recommendations and the divers' frequent requests, and as an urgent response to conserve the remains stock, the abalone fishery should be closed for 3-5 years to conserve the remaining stock, rebuild the adult population to a much higher level and avoid the collapse and extinction of this species from the Omani waters. Divers should be notified early and given the last fishing season before taking this action, to arrange their yearly financial obligations, as most of them are indebted to the traders and their payment depends on what they can gain during the fishing season. Creation of new job opportunities in these areas or provision of subsidies will help to reduce the unemployment levels and hardship.

Option Two: Increase MLS limits, and reduce fishing season period

As mentioned above, the Minimum Legal Size of (90 mm SL), introduced to allow abalone the opportunity to breed at least once before it enters the fishery, was not strictly enforced. This minimum size limit is defined at a size where most abalone are two years older than the size at which most become sexually mature.

Since the level of fishing effort on the stock is very high, and most of the abalone below this size are taken by divers, it is necessary to have an even larger minimum size limit to ensure that adequate egg production is protected. Shepherd *et al.*, (1995) suggested that maintenance of egg production levels of at least 40% would require a size limit of between 105 and 115 mm SL at the present high levels of fishing mortality. Large minimum size limits can also help to reduce the size of catch. Moreover, in all cases the fishing season must be changed to between March and May, based on this study. In addition, limiting the fishing season length to one month will be of benefit for conservation of the resource. The introduction of these control measures as part of a strategy to reduce the overall catch would not be effective without adequate enforcement.

Option Three: Partiall closure of the fishery (Rotation system or Rolling closure)

Massive habitat destruction in many fishing grounds as well as heavy depletion of the stock is prevalent. Therefore, these areas need to be rested to recovere from this situation and the stock needs to be rebuilt. If it is not possible to close the whole fishery, then at least the affected areas should be closed using a rotation system, and the local community should be involved in the monitoring of these areas in cooperation with the fisheries authority. This option should be strengthened with a real and effective monitoring system as well as law enforcement to achieve its aims.

Option Four: Limiting divers' access (Licence system)

The unavailability of access control system for this fishery makes it easy for any one to be involved in the diving activities, and as this fishery is open access and due to its high value, the number of divers has gradually increased each year. As a result, the number of divers is now beyond the capacity of this resource, and most of the divers are from other regions. Therefore, it becomes more important in this fishery to impose limitations on diving activities through the control of diver access via the introduction of diver licensing system. This will help to identify the divers and give more control on the fishery as well as on the monitoring and observation of divers' activities. It will also provide reliable data and records about the effort on this fishery. Thus, this option is likely to help to reduce of number of divers and prevent outsider exploitation of this fishery.

The implementation of any or more of these options would have serious short-term social and economic implications but in the long run these would be less than those brought about by the total collapse of the fishery. In addition to the above options, Co-management is seen as the best way to manage this resource. A proposal toward co management is proposed below:

Toward Co-management and improvement of MCS system

This fishery faces a significant problem that has escalated over the last few years. The combination of increasing numbers of divers and the open access nature of this fishery, associated with lack of law enforcement, contributes to increased over-fishing and depletion of the resource, as well as destruction of abalone habitat.

Currently, landing of illegal sizes exceeds 50% of annual catch, most of the diving operations take place in shallow waters below the legal defined depth as well as out of season, and turning over the boulders and rocks is a common diving practise, which results in environmental destruction and habitat losses. The current management system has failed to monitor, control and exercise surveillance over the resource and users' activities in a proper way, and therefore to manage and protect the resource, which will have significant impact on the sustainability of the resource as well as a future impact on coastal communities dependant on this resource. Thus, it is necessary and essential to develop and introduce a new management plan to prevent further destruction of this fishery.

Managing this fishery without involving local communities is considered to be one of the reasons behind this failure, due to lack of participation and cooperation of resource users. A more dynamic and flexible partnership with resource users is needed, using the capacities and interests of local divers and community, complemented by the ability of the fisheries authority to provide enabling scientifically-based legislation, strong law enforcement and other requirements and assistance, specifically co-management. Co-management will help to achieve joint responsibility and authority for abalone management through cooperation between the Ministry and local resource users, which will harmonize the traditional approaches to fisheries management with fisheries legislation. This is likely to result in the community acceptance of this legislation. It will encourage community participation in actual implementation of the management plan, and hence, voluntary compliance with it.

This action will require development of a foundation for co-management and building relationships with all groups and opening channels of communication between resource users and the fisheries authority. The existing fisheries committee (Sonnat Al'bahar) in each region could be developed and used to represent the local community and to co-ordinate the relationship between resource users and the authority. Increasing awareness should be built around resource management and local management plans for abalone resources.

The implementation of co-management, however, will require securing the access rights for the local divers, which could be achieved through the introduction of a licensing system. This is important also to identify the local users of this resource and prevent participation by divers from other regions. In addition, this will help provide information for monitoring, controlling and surveillance of the fishery activities.

The abalone fishery in Oman is not very complicated to be managed compared with other abalone fisheries with multi users such as in South Africa. Coastal monitoring, controlling and surveillance (MCS) can be seen as one of the best ways to achieve integrated implementation of participatory management plans. The current monitoring, controlling and surveillance system needs to be improved through effort and attention from the management authority and more cooperation with the local community by their involving them in the MCS. This could be achieved through:

- Education of communities in management and monitoring, controlling and surveillance system processes through public awareness campaigns, seminars at school, local fishers meetings and specific training. This will result in a better understanding of the requirement for MCS activities and community-accepted legislation measures to support the management plan. This also will encourage voluntary compliance with the management plan and therefore compliance with the laws voluntarily;
- An awareness campaign should take place in the divers' community to explain the serious situation of the fishery and present the results of this study, illustrating the recent relating problems and the implications of the wrong practice of some divers on the future of the whole community.
- Establishing local resource management organizations and placing abalone areas under their conservation management;
- Ensuring that communities are consulted and involved in management planning and during the process of drafting local legislation, by-laws and ordinances needed to implement the management plan;
- Considering MCS options that directly support conservation of abalone resources, such as licensing/registration, data collection, community involvement, and staff training in the coastal resource management plan;
- Providing a sufficient annual budget to cover MCS implementation;

- Developing and implementing fisheries and coastal management legislative instruments such as a licensing system to support the implementation of MCS system.
- Developing and training coastal law enforcement teams, providing them with appropriate and needed facilities and bringing them into operation;
- Instituting resource watch networks or a reef watch programme that follow the same general principles as an observer programme to observe, record and report, but to take no direct enforcement action.

Individuals assigned to participate in reef watch programmes should be utilized only in observation and to provide information to the community and authorised law enforcement personnel to take appropriate follow-up enforcement action, and should not have enforcement authority.

Improving current monitoring, controlling and surveillance system for Haliotis mariae fishery

A data collecting system for abalone management that includes information on divers' fishing effort, area of operation and landings exists. However, this needs to be developed to include information on other diving activities and to be monitored through a network of full-time or part-time, well-equipped data collectors at the landing sites during the fishing season. The fishery could then be monitored through the collecting, measuring, analysing, and reporting of this information, which are necessary for fisheries management decisions.

To control the fishery, it is necessary to enforce the law, and apply the existing regulations and legal administrative measures, such as diving rights, the minimum legal size limit, fishing season, defined diving depth, use of SCUBA, and prevent destruction of environment and resource habitat.

Achieving the implementation of control measures requires surveillance and regular observation on the resource to maintain compliance with the regulatory controls and to detect and deter fisheries violations, as well as to apprehend illegal divers, traders and all types of law breakers, such as those collecting the small immature sizes, turning over the boulders, and diving out of the season.

The existing penalties in the law such as fines, confiscation of fishing gear, jailing and expilsion from the sector should be strongly applied to deter and hinder the illegal fishing and violation of the regulations. This is critical to reduce overexploitation of the stock and to ensure that landing of small sizes and diving activities out of season are minimized.

More recommendations to the management of this fishery are proposed in Chapter 7. These recommendations should be taken into account when applying any of the above management options.

6.2.8 Conclusions

Considering the status of the abalone fishery in Oman with the high commercial value of the product and the depletion of many fishing grounds, it is likely that the remaining abalone stocks will be put under greater pressure. The reasons for stock decline are varied, but they are mainly linked to unwise management and inadequate enforcement policies, which have resulted in the over-exploitation of the resource. Major changes can occur in abalone populations as a result of natural events or human activity. Moreover, shifts in currents, temperature changes, flood sedimentation, yearly mass mortality of sardine in inshore costal water, variation in the seasonality of food sources, which are associated with the monsoon season, together with the effect of associated animals, can influence and alter abalone environments and disrupt their biological systems.

The irresponsible divers' activities increase the potential to accelerate the loss of abalone resources. Some activities, such as over-fishing, catching the small immature abalone and destruction of abalone habitats, have been occurring for many years. Serious depletion in abalone habitat has already been observed in many areas. The absence of a strong enforcement policy, evidence of poaching, and strong activity of illegal fishing constitute a situation where there is a significant threat to the stocks and sustainability of the fishery.

Fisheries policies and regulations that control abalone resources could make important contributions to conserving abalone fishery if they are in place and such measures might prevent continued decline in the stock. Unfortunately, no concern has been given to the serious status of the fishery. If the present situation continues, the abalone fishery, which is threatened, will collapse and this valuable resource could disappear from this region within the coming few years.

Moreover, because the current status of the fishery will not fall to growth-over-fishing if the present legal size (90 mm SL) of capture is not strictly enforced, appropriate measures such as awareness campaigns, enforcement of shell length restrictions, and improvement of the fisheries management system, are indispensable. At the same time, as a mid and long-term objective, there is a need to understand the factors affecting recruitment dynamics of the stock.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This study seeks to address the knowledge gaps in the abalone (*Haliotis mariae*) fishery of the Sultanate of Oman. Different aspects of the ecology and dynamics of the abalone were examined and information on the fisheries distribution, abundance, morphometry and size composition structures, habitat, competitors, predators, commercial production and marketing, biochemical composition, environment parameters, preservation, genetics, biology including growth, reproduction, spawning season, sex distribution, maturity stages, size at first maturity, and stock status are now available. Collation of commercial catch statistics allowed assessment of trends in the fishery production and to make inferences about the relative availability of this species to commercial divers. Monitoring of the sizes of abalone being landed by commercial divers has also provided indicators of resource status and baseline information on from which future assessments may be based. The available information will serve as guidance for the management of this important resource as well as a basis for future studies. The outcomes of this study are summarised below in relation to the status of the fishery and recommendations to manage this resource are proposed.

The southern coast of Oman is influenced by the monsoon season between June and September each year. The environmental parameters along this coastline showed major changes during this period, which occurred largely as a result of upwelling of deep cold nutrient-rich water, when the water temperatures drops to 18 °C in August. The maximum development of flora is apparently restricted to this season when the upwelling is most pronounced, and when the nutrients essential to the flora are available. The brown algae forest such as kelp and *Sargassum* can be found along the coastline between Mirbat and Sharbithat for only a short period after the monsoon season. This is in contrast to all the upwelling-induced kelp ecosystems known from other parts of the world, where these algae can be found throughout the year (Barratt *et al.*, 1984). These algae communities are known to be highly productive, supplying cover and food for commercial important species distributed in the rocky shores along this coastline, such as abalone.

The sedimentation and organic materials brought from land to coastal waters during the rainy season (monsoon) resulted in low oxygen levels in the semi-closed bays due to the decomposition of organic items. This is thought to influence the settlement and survival of abalone larvae, which are usually associated with the shallow waters, and reduce the growth rate of animals in such areas.

The presence of oxygen poor water in the inshore water has been suggested as an environmental stress and as a possible cause behind the yearly mass mortality of Sardine that occurs along this coast, which has an effect on the abalone stock and their habitat. These factors are thought to have some impact on the availability and distribution range of abalone population, as well as the depletion of abalone stock in some areas.

The commercial fishery for *H.mariae* during the last few years was based almost exclusively on small sizes (around 50% of the diver landings were < 90mm SL). The sizes of *H. mariae* in diver landings were consistent between years and between locations. This consistency is likely to have been a result of the unavailability of large sized individuals, especially in Mirbat and Hadbin. Analysis of diver landings at the three main commercial landing sites during the 2003 fishing season indicated that divers' catch contained mostly small sizes below the Minimum Legal Size of 90 mm (MLS). *H. mariae* were, on average, smaller in diver landings taken from Mirbat and Hadbin (88.2 mm and 90.4mm SL) respectively, compared with those from Sharbithat (98 mm SL). Mirbat and Hadbin divers' landings had 57.7% and 50.5% below the MLS of 90 mm SL respectively, whereas relatively larger sizes were seen in Sharbithat, with only 26.3% below this limit. Thus, overall, 44.8% of the catch was below the MLS. The case of Sharbithat was likely due to the smaller numbers of divers operating in this area, which may reduce competition among them and allow for more selectivity in their catch. Moreover, even though the sex distribution in the diver landings followed the 1:1 ratio, females show slightly higher numbers, and most of the animals landed at the three areas were observed to be in their final maturity stage and ready to spawn, which supports other findings in this study, and indicates the serious situation of the fishery.

Abalone morphometry varied within and among populations at the three permanent study stations (Mirbat, Hadbin and Sharbithat). Mean shell length of monthly samples from Sharbithat exceeded mean shell length of those of Mirbat and Hadbin, which was much less than the MLS of 90 mm. The difference in the size composition between the three sites was also reflected in the size composition of divers' catch from the three populations during the fishing season. Changes in morphometry are particularly related to environmental conditions and food availability associated with the monsoon season.

The size composition of the samples varied slightly among sites and with time. The range of most samples collected from Hadbin and Mirbat extended below the minimum legal size (MLS) of 90 mm, and only a few individuals exceeded 120 mm SL. However, in Sharbithat there were more large sizes, but with lower flesh weight. This variation in size composition among the three sites is most likely due to the unavailability of large size specimens, which seems to be linked with the more rapid increase in fishing pressures during the last few years at Hadbin and Mirbat.

The sex ratios deviate slightly from the expected ratio of 1:1, indicating distribution of more adult male than female abalone in the population. This was probably because females are larger and fishing pressure on them was greater. This result is consistent with sex distribution in divers' landings, which showed the opposite trend and indicated of more females than males. This low level of females may impact on future recruitment.

H. mariae breeds once per year, around the time when water temperature declines during November to January. Gonad maturation is affected by the availability of food and changes in water temperature. Sexual maturity of *H. mariae* could be classified into four stages: stage zero which represents no development and sex cannot be distinguished and determined, and three later developmental stages. The occurrence of advanced mature stages between November and April is evidence of the spawning season, which is restricted to the same time at all the three sites.

The size at first maturity for *H. mariae* was reported by Shepherd *et al.,* (1995) at 75 mm SL. With the recent heavy landing of small sizes, it seems that most of the divers' catch has not reproduced even once, which has a huge impact on recruitment to the fishery.

The growth rates reported for this species vary among studies; they grow at 43 mm in the first year and 20-25 mm in the second and third year with an annual average of 23 mm SL (Shepherd *et al.*, 1995) or may be up to 36 mm/year (Stirn & Al-Hashmi, 1996). Fishing mortality of this fishery is very high and egg production level is very low (Siddeek & Johnson, 1993; Shepherd *et al.*, 1996).

Biochemical composition of foot muscle of male and female abalone from the three areas showed the same trend with both sexes, and no significant differences in the proximate composition was found among the three sites. However, there were gradual increases in moisture, protein, fat, ash, and carbohydrate values from December to June and July and then a decrease toward October and November, suggesting biochemical composition of foot muscle is influenced by the seasonality and availability of food sources and temperature, which has an impact on the spawning season. In addition, the combined results of biochemical composition and gonad development for *Haliotis mariae* indicate that the gradual decline in these values is due to energy utilized in the gonad development and suggests that the spawning season occurs between November and February, which is in accordance with previous findings (Sanders, 1982; Savidge *et al.*, 1986)

Considering dried abalone is the most common export form of Oman abalone, this preservation method is traditionally used by the abalone traders. In order to estimate the losses in weight during this process, an abalone drying experiment was conducted. The final dried weight of the product was only 35% of the initial weight of the foot muscle. This percentage decreased more with small sizes below the legal size by 1% or more compared with large sizes. The optimum drying time was estimated to be between 7-10 days to obtain a high quality dried product. Therefore, the traders can minimize their preservation cost in terms of drying expenses and labour charges, by reducing the drying period to this limit. Moreover, financially, although the weight loss percentage is very small, because most production is of small sizes, abalone traders are making some loss by purchasing illegal sizes. In addition, the traders indirectly contribute to destruction of this resource by encouraging divers through acceptance of their small size catch.

The geographical range of *H. mariae* was found to be restricted to the exposed typical rocky shores dominated by availability of algae cover along the coastline between Ras Zuhair at Mirbat and Hasik, and in some rocky shores around Sharbithat and Soqrah. The species was distributed in both intertidal and subtidal zones, but it varied among the five surveyed areas. Small numbers of abalone were found in the intertidal zone, but the population occurs mainly between the low water mark and a maximum depth of 20 metres. Small and medium sizes individuals mostly occur in the shallow waters below 5 metres depth, whereas relatively larger sizes occur in much deeper waters ranging between 5-10 metres. Few individuals were found in the deeper water below 15 m.

Abalone was more abundant at Hadbin, Sadah and Mirbat than Hasik and Sharbithat, but the remaining stock in Mirbat and Hadbin consists mainly of small sizes. In contrast medium and large sizes were found at Sharbithat. The mean sizes were low than the MLS (90 mm SL) at all sites. Generally, *H. mariae* were never observed in aggregations, and only individuals were observed. The density was low, about 0.07 individuals/m^2, which is much less than that reported by Sanders (1982) at an average of 0.205 individual/m^2. The preliminary abalone stock is estimated at 707,000 individuals, equivalent to 54.5 t of flesh.

Haliotis mariae habitat varied among the surveyed areas. Mirbat and Hasik abalone habitats consist mainly of rocks with some small and medium sized granite boulders ($\leq$ 1-2 m), whereas greater variation in the presence and sizes of these boulders ($\leq$1-5 m) combined with some areas of flat rocks was found at Sadah, Hadbin and Sharbithat. Most of these boulders and rocks have been overturned, and many habitats in all the surveyed areas have been destroyed. This is thought to be a result of the incorrect practice of some divers turning over these boulders and rocks during their search for abalone. These boulders are later polished by the currents and strong water movement during the severe rough sea associated with the monsoon, resulting in major changes in the ecosystem and abalone environment. As a result, the vegetation cover has gradually declined, causing a lack of food sources for abalone, except during the monsoon season.

Sea urchins were the dominant macrofauna in this habitat. Urchin density was recorded at 1.8 individuals/m^2, which is about 25 times the number of abalone. This indicates a significant change in their abundance compared with that recorded by Ogawa (1994) at 6 times the number of the abalone. Considering this animal is a major competitor for food and living space with abalone, this rapid increase will have an impact on the abalone stock. Moreover, extensive grazing by both abalone and sea urchin has been observed in the surveyed areas. This intensive and excessive grazing causes the Isoyake phenomenon, with deteriorating food sources, especially when food is scarce, as algal availability is associated only with seasonality of the monsoon.

Various predators have been recorded in the abalone habitat, especially sea star, which is thought to have some effect on the abalone population. A new type of diver-made predation on abalone larvae and early stage juveniles was observed through the wrong practice of turning over the boulders and rocks, which also allows fish to attack and prey on these cryptic animals.

Genetically the populations of *Haliotis mariae* at Mirbat Hadbin and Sharbithat were similar, but these populations differ considerably from other species of *Haliotis* worldwide. No close match of the *Haliotis mariae* species was detected in the GenBank analysis. Hence, it can be assumed that no sequence data were available for this species and this is the first attempt to characterize genetically the *Haliotis mariae* species globally.

Although the management of the fisheries sector in Oman has realized much progress during the last twenty years, management of the *Haliotis mariae* fishery is still in flux and has failed to protect the over-exploited stock. The institutional and legal limitations, as well as the insufficient scientific background and lack of implementation and enforcement of the law and regulations, could be considered as the main reasons behind this failure to protect and conserve this resource.

7.2 Recommendations

Based on the present analysis, together with the data available to date, the following recommendations are suggested to improve management of the resource and to achieve the sustainability of this lucrative species, unique to this country in the Arabian Peninsula.

- The recent fishing season must be changed and relocated in light of the exact spawning season; the new fishing season is suggested to be between March and May. Also the fishing season needs to be reduced to one month to conserve the endangered and overexploited fishery, which is already on the edge of extinction.
- Continued prohibition of the use of any kind of diving gears is very important to conserve whatever deeper water stocks might exist.
- Abalone habitat areas that have been destroyed can be improved while closing the season through relocating rocky habitat and artificial reef beds. This might encourage the abalone to attach themselves to these beds.
- Abalone can be transplanted and introduced to the destroyed areas along the southern coastline; East and West Mirbat, around Sadah, East Hadbin, around Al'Halaneyiat Islands, around Sharbithat and Soqrah, or even introduced to new areas along the same coastline. These individuals should be sourced from local stocks.
- Abalone stocks could be enhanced through releasing the artificially produced seeds of abalone. This is quite difficult at the present time due to the limited production of Mirbat Abalone Seed Production Station, which has very limited facilities and has been without any maintenance for a long time. But it is relatively important to improve these facilities to increase the future production of this station to enhance the over-exploited stock, and to help in the development of aquaculture industry in Oman.
- Encouragement of investment in aquaculture projects and providing investors with logistic, technical, and financial support will help establish an aquaculture industry, which will be beneficial to the community, the country's economy, and the fishery itself, through the contribution of these hatcheries in stock enhancement.

- A special and standard abalone lifting tool with size limit gauges should be designed and introduced by the Ministry to reduce the abalone cut when removing from the rocks and minimize the sub-legal mortality. This may also reduce the sub-legal catch.
- Establishment of a more effective system of training and education needs to be put into effect, and the importance of this species together with the problems facing it could be introduced in the education curriculum.
- Press and media campaigns should be used to get the attention of the public and concerned bodies about the importance of this fishery and the problems that threaten it.
- Strong cooperation should be established between the Fisheries Authority and different related Government Departments in the region such as the Royal Oman Police, Governor Office, Coast Guard, and Ministry of Environment, as well as the fisheries' local community council (Sonaat Al'Bahar) to help in monitoring the fishery against the law breakers. The export of this product should be strictly regulated, and the export points should be strongly monitored. The abalone traders should be monitored and prosecuted for buying and trading undersized abalone, this should be a management start point.
- The local species should be protected by banning live export of *Haliotis mariae* for commercial use.
- Rewarding community participants who help in applying the law among the areas might encourage other communities to follow the same way.
- The data collecting system should be improved by applying an adequate number of trained and qualified data collectors, as most of the previous collected data depend on estimation rather than exact reading.
- A diving campaign could be carried out to gather the abalone individuals and bring them close to each other in protected sites to increase fertilization rate and rebuild the stock.
- Considering the existing market for abalone shells, it is desirable to find the best way of utilizing the discarded shells by searching for international markets and directing the divers and traders for more benefit and to improve their income.

- Intentional or inadvertent transfers and introduction of abalone species into new environments have occurred widely during the past century. Often the transfers or introductions have been related to management actions intended to benefit human societies. Although some transfers have resulted in economic benefits, others have had devastating effects on the natural resources of other species. Therefore, the introduction of any new abalone species to Oman is not recommended, but in case of doing so, it is very important to implement restricted control and monitoring measures to avoid any impact on the wild stock.

7.3 Further Research

Further research is needed to understand the interactions between abalone and its surrounding environment. Important research topics are suggested as below.

- When closing the fishery or introducing any new measures it is important to evaluate their effects. Therefore, continued research and surveys are needed to estimate the changes in the stock structure before reopening the fishing season, together with studying other aspects of the fishery. This will be a good way to understand how the status of the fishery changes over time in relation to management interventions.
- As there are no previous studies on sea urchin, and due to its great abundance in the abalone habitat and interaction with abalone, it is recommended to undertake a complete research programme to cover different aspects of sea urchin biology and control. This will allow better understanding of the interactions between sea urchins and abalone and improve management decisions for both species groups. It is also possible that markets can be found for the sea urchin. If so, then a feasibility study should be carried out, and a good market sought; and the divers provided with training and techniques for fishing this species. This might be a good solution for more than one problem.
- A similar project should be undertaken on sea stars as a major predator of abalone, to better understand predator-prey relationships.
- It is very important to study the socio-economic aspects of the abalone divers to formulate appropriate fishery management measures.

- More studies are recommended on marketing to find the best export product forms and preservation methods for value added.

It is important to know that the seas will continue to produce only if the resource is conserved, as well as the habitat itself. If this approach is followed, the stock will be maintained and the future of the fishery will be ensured; otherwise, collapse could be imminent.

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APPENDIX

Internationally published sequence Data References:

Haliotis corrugata

LOCUS AY679070 535 bp DNA linear INV 28-JUL-2004

DEFINITION Haliotis corrugata isolate Hco03 Cytochrome oxidase subunit I (COI) gene, partial cds; mitochondrial.

ACCESSION **AY679070**

VERSION AY679070.1 GI:50546342

SOURCE mitochondrion Haliotis corrugata (pink abalone)

ORGANISM Haliotis corrugata

REFERENCE 1 (bases 1 to 535)

TITLE Phylogenetic analysis of commercial abalone species from the Pacific Mexican Coast

JOURNAL Unpublished

REFERENCE 2 (bases 1 to 535)

AUTHORS de la Rosa-Velez,J., Velazquez-Magana,S. and Enriquez-Paredes,L.

JOURNAL Submitted (06-JUL-2004) Facultad de Ciencias Marinas, Universidad Autonoma de Baja California, Km 103 Carretera Tijuana-Ensenada,

1 acttagtctt ttaattcgag ccgaacttgg ccaaccaggg gcacttctag gagatgacca
61 actctacaat gtaattgtaa cagctcacgc tttcgtaata attttcttcc tagtcatgcc
121 actaataatc ggaggatttg gaaactgatt agtcccccta atacttggtg caccggatat
181 agcttttccc cgattaaata acataagatt ctgactcctt ccgccatcct taaccttact
241 cttaacatca ggcgctgtag aaagcggggc aggaacaggc tgaacagtct accctcccct
301 ttctagtaac cttgcccacg caggagcatc agtcgacctt gcaattttct ccctacacct
361 agccggaatc tcatcaattt taggggcagt aaattttatc actacagtaa taaatatgcg
421 tgtaaaagca caacctttag aacgaatacc attatttgtt tgatccgtaa aaattactgc
481 catcttactt ctcttatcac tacctgttct agcaggtgct attacaatac tttta

Haliotis discus

LOCUS AY146398 544 bp DNA linear INV 01-MAR-2003

DEFINITION Haliotis discus Cytochrome c oxidase subunit I (COI) gene, partial cds; mitochondrial gene for mitochondrial product.

ACCESSION AY146398

VERSION AY146398.1 GI:28627832

SOURCE mitochondrion Haliotis discus

ORGANISM Haliotis discus

REFERENCE 1 (bases 1 to 544)

AUTHORS An,H., Lee,Y., Min,K., Han,S., Kim,B. and Won,S.

TITLE Phylogenetic relationship of pacific abalone based on mitochondrial COI gene sequences

JOURNAL Submitted (29-AUG-2002) National Fisheries Research and Development Institute, 408-1, Sirang-ri, Kijang-up, Kijang-gun, Busan 619-902,Korea

1 gtctcttaat tcgagccgaa cttggccaac caggggcact tttaggggac gaccaactct
61 ataacgtaat cgtaacagcc cacgctttcg taataatttt cttcctagtt atgccactaa
121 taattggagg atttggaaac tgattagtcc ccctaatact gggagcaccg gacatggctt
181 tccccc gact aaataacatg agattctgac tcctcccacc atccttaact ctgctcttaa
241 catcaggcgc agtagagaga ggagcaggga caggctgaac agtctatccc cccctctcta
301 gtaaccttgc ccatgcagga gcatcagtag acttagcaat tttctcccta cacctagccg
361 gaatctcatc aattttaggg gcagtaaact ttatcactac agtaataaat atacgtgtga
421 aagcacaacc tctagaacga ataccattat ttgtttgatc agtgaaaatt actgccatct
481 tattactctt atcactgcct gttctagcag gtgctattac aatactccta accgaccgta
541 attt

Haliotis iris

LOCUS AF060854 524 bp DNA linear INV 03-SEP-1998

DEFINITION Haliotis iris Cytochrome c oxidase subunit I (COI) gene, mitochondrial gene for mitochondrial protein, partial cds.

ACCESSION AF060854

VERSION AF060854.1 GI:3108132

SOURCE mitochondrion Haliotis iris

ORGANISM Haliotis iris

REFERENCE 1 (bases 1 to 524)

AUTHORS Metz,E.C., Robles-Sikisaka,R. and Vacquier,V.D.

TITLE Nonsynonymous substitution in abalone sperm fertilization genes exceeds substitution in introns and mitochondrial DNA

JOURNAL Proc. Natl. Acad. Sci. U.S.A. 95 (18), 10676-10681 (1998)

JOURNAL Submitted (22-APR-1998) Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093, USA

1 gtctcttaat tcgagccgaa cttgggcagc ctggcgctct tttaggggac gaccaactgt
61 acaatgtaat tgtaacagcc catgcttttg tgataatttt ctttctagtc atgcccctaa
121 taattggcgg attcggtaac tgacttgtcc cactaatatt aggcgcacca gatatggctt
181 ttcctcgact caacaacata agattttgac tacttccccc atccctaact cttctcctaa
241 catcaggagc cgtagaaagc ggtgcaggga cagggtgaac agtttaccct cctttgtcta
301 gtaaccttgc ccatgcaggc gcatccgtag accttgcaat tttctcccta cacttagccg
361 gaatctcatc aatcctagga gctgtaaact ttatcaccac agtaataaac atacgagtaa
421 aagcacagcc cctagaacgg atacctttat tcgtctgatc cgtaaaaatt accgccattc
481 tacttctcct atccctccct gtccttgcgg gagccattac aatg

Haliotis rufescens

LOCUS AF060843 520 bp DNA linear INV 03-SEP-1998

DEFINITION Haliotis rufescens isolate ME2 Cytochrome c oxidase subunit I (COI) gene, mitochondrial gene for mitochondrial protein, partial cds.

ACCESSION AF060843

VERSION AF060843.1 GI:3108110

SOURCE mitochondrion Haliotis rufescens (California red abalone)

ORGANISM Haliotis rufescens

REFERENCE 1 (bases 1 to 520)

AUTHORS Metz,E.C., Robles-Sikisaka,R. and Vacquier,V.D.

TITLE Nonsynonymous substitution in abalone sperm fertilization genes exceeds substitution in introns and mitochondrial DNA

JOURNAL Proc. Natl. Acad. Sci. U.S.A. 95 (18), 10676-10681 (1998)

JOURNAL Submitted (22-APR-1998) Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093, USA

1 ctcnntcttt taattcgggc cgaacttggc cagccagggg cactcttggg ggatgaccaa
61 ctctataacg taattgtaac agcccacgct ttcgtaataa tcttcttcct agttatacca
121 ctaataattg gagggtttgg aaactgacta gtccctttaa tattaggggc accagacatg
181 gcttttcccc gactaaataa cataagattc tgactccttc cgccatcctt aaccctactc
241 ctaacatcag gcgctgtaga aagaggggcg ggaacgggct gaacagtcta ccctcccctc
301 tctagtaacc ttgcccacgc aggagcatca gtagacttag caattttctc cctacaccta
361 gccggaatct catcaatttt aggggcagta aactttatta ctacagtaat aaatatacgt
421 gtaaaagcac agcccctaga acgaatgcca ttatttgttt gatcagtaaa aattaccgcc
481 atcctactac ttctatcact acctgttnta gcaggtgcca

Haliotis tuberculata

LOCUS AY377729 637 bp DNA linear INV 03-FEB-2004

DEFINITION Haliotis tuberculata Cytochrome c oxidase subunit I (COI) gene, partial cds; mitochondrial.

ACCESSION AY377729

VERSION AY377729.1 GI:38607151

SOURCE mitochondrion Haliotis tuberculata

ORGANISM Haliotis tuberculata

REFERENCE 1 (bases 1 to 637)

TITLE Towards a phylogeny of chitons (Mollusca, Polyplacophora) based on combined analysis of five molecular loci

JOURNAL Org. Divers. Evol. 3 (4), 281-302 (2003)

AUTHORS Okusu,A., Schwabe,E., Eernisse,D.J. and Giribet,G.

JOURNAL Submitted (01-SEP-2003) Organismic & Evolutionary Biology, Harvard University, 16 Divinity Av., Cambridge, MA 02138, USA

1 ggatctgatc agggctcctt ggactgccct gagtctccta atccgagcag agctcggaca
61 accaggagca ctcctaggag acgatcaact ctataatgta attgtaacag cccacgcttt
121 tgttataatt ttctttctag ttataccact tataattggc ggatttggga actgactagt
181 tcccttaata ctcggagcac cagacatggc ttttcctcgc ctcaacaaca taagattctg
241 acttctccct ccctctctta ccctcctatt aacatcaggt gccgtagaga gcggtgcagg
301 aacaggatga acagtctacc cgcccctatc aagtaacctt gctcacgcag gagcatcagt
361 agatcttgca atttttcac ttcacttagc cggaatctcc tcaattctcg gagcagtcaa
421 tttcattact acagtcataa atatacgagt aaaagcgcaa cccttagagc gaatgccttt
481 atttgtttga tcagtaaaaa ttacagctgt gcttctactt ctctctctcc cagttcttgc
541 tggcgcaatc acaatacttc taactgaccg taacttcaat acctcattct ttgacccagc
601 agggggagga gaccctattc tatatcaaca cctattc