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ENVIRONMENTAL IMPACT ASSESSMENT OF SUSPENDED OYSTER, *CRASSOSTREA MADRASENSIS* (PRESTON) CULTURE

Thesis submitted in partial fulfillment
of the requirements
for the degree of

DOCTOR OF PHILOSOPHY
In Fish and Fisheries Science
(Mariculture)

of the

CENTRAL INSTITUTE OF FISHERIES EDUCATION
(Deemed University)
Versova, Mumbai – 400061

by

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AUGUST 2006

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CERTIFICATE

Certified that the thesis entitled **"ENVIRONMENTAL IMPACT ASSESSMENT OF SUSPENDED OYSTER, *Crassostrea madrasensis* (Preston) CULTURE"** is a record of independent bonafide research work carried out by **Mr. Ramalinga (PhD - 133)** during the period of study from October 2000 to August 2006 under our supervision and guidance for the degree of **Doctor of Philosophy** in **Fish and Fisheries Science (Mariculture)** and that the thesis has not previously formed the basis for the award of any degree, diploma, associateship, fellowship or any other similar title.

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I hereby declare that the thesis entitled **"ENVIRONMENTAL IMPACT ASSESSMENT OF SUSPENDED OYSTER, *CRASSOSTREA MADRASENSIS* (PRESTON) CULTURE"** is an authentic record of the work done by me and that no part thereof has been presented for the award of any degree, diploma, associateship, fellowship or any other similar title.

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Ramalinga

सारांश

लगातार पांच वर्षों के दौरान भारत की पश्च जल शुक्ति *क्रासोस्ट्रिया माड्रासेन्सिस* (प्रेस्टन) के पालन से होने वाले पर्यावरणीय संघातों पर अध्ययन किया गया. तीन, छह और महीने की फसल छुट्टी अवधि के दौरान हुए परिवर्तनों पर भी अध्ययन किया गया. विभिन्न पालन स्थानों में पालन समय और फसल छुट्टी अवधि के समय जल स्तंभ, अवसाद की विशेषताओं और नितलस्थ स्थूल प्राणिजातों में हुए परिवर्तन की तुलना अध्ययनाधीन पालन स्थानों के साथ की गयी. अध्ययन से यह संकेत मिलता है कि लगातार पालन करने से जलराशिकी प्राचलों में उल्लेखनीय परिवर्तन नहीं होता है. लेकिन विशेषताओं और नितलस्थ स्थूल प्राणिजातों पर लगातार पालन का प्रभाव पड जाता है. एक वर्ष के पालन से कच्चे और साफ रेत के प्रतिशत में घटती और सिल्ट, कीचड और ओर्गानिक कार्बन के प्रतिशत में बढ़ती देखी गयी. दो वर्ष के पालन से होनेवाले अवसाद विशेषताओं के संघात को छह महीनों की फसल छुट्टी देने से सुधार किया जा सकता है. लेकिन पांच वर्षों के लगातार पालन से होने वाले संघात को नौ महीने की फसल छुट्टी देने पर भी सुधार नहीं किया जा सकता. खेत के और अध्ययनाधीन स्थान के नितलस्थ स्थूल प्राणिजात की मात्रा एक वर्ष की पालन अवधि के दौरान भिन्न भिन्न देखी गयी. पालन के पहले वर्ष में पालन स्थान और अध्ययनाधीन स्थान में होनेवाली जीव जातियों की संख्या बराबर (पालन स्थान में 30 और अध्ययनाधीन स्थान में 28) देखी गयी. पालन के दूसरे वर्ष की अवधि में रिकार्ड की गयी मछली जातियों की संख्या पालन स्थान में 24 और अध्ययनाधीन स्थान में 33 थी लेकिन यह अंतर इतना महत्वपूर्ण नहीं है. इसके विपरीत, पांच वर्ष के पालन में पालन स्थान और अध्ययनाधीन स्थान की मछली जातियों की संख्या में उल्लेखनीय अंतर दिखाया पडा था. पालन स्थान की अपेक्षा अध्ययनाधीन स्थान की मछली जातियों की संख्या अधिक थी. पालन के प्रथम वर्ष तक शुक्ति पालन किया जा सकता है और अगर दो वर्ष अधिकतम जीव (1278 m^{-2}) और चौथे वर्ष न्यूनतम (279 m^{-2}) जीव दिखाए पडे. फसल छुट्टी के अवसर पर पालन स्थान में होनेवाली जीव जातियों और जीवों की संख्या में सुधार हो गया. यह भी साबित हो गया कि दो वर्ष के शुक्ति पालन से होने वाले संघात को सुधार करने केलिए फसल छुट्टी देना ज़रूरी है. वर्तमान अध्ययन के निष्कर्षों के आधार पर यह सुझाव दिया जाता है कि लगातार दो वर्ष से ज्यादा पालन करना है तो कम से कम छह महीने की फसल छुट्टी देना अच्छा होगा. दो वर्ष के पालन के बाद नालन स्थान बदलना भी बेहत्तर है.

ABSTRACT

The environmental impact due to farming of the Indian backwater oyster *Crassostrea madrasensis* (Preston) for five consecutive years was studied. The changes during crop holiday periods of three; six and nine months were also assessed. The water column and sediment characteristics and benthic macrofaunal community changes of farm sites of different farming and crop holiday periods were compared with those of reference sites. The study indicated that there were no significant variations in the hydrographic parameters due to continuous farming. However, the sediment characteristics and the benthic macrofaunal composition at the farm sites were found to change with continuous farming. The percentage of coarse and fine sand was found to decrease while that of silt, clay and organic carbon found to increase with the year of farming. The impact on sediment characteristics due to farming for two years could be rectified with a crop holiday of six months period but the impact due to continuous farming for five years could not be rectified even with a long-term crop holiday of nine months. The benthic macrofaunal communities of the farm and reference sites were found to vary with the year of farming. The number of species recorded at the farm and reference site of first year of farming was almost similar (30 for farm site, 28 for reference site). The number of species recorded for the second year farming period was 24 for farm site and 33 for reference site, but the difference was not significant. On the contrary, significant differences were found in the number of species at the farm and reference sites of three, four and five years of farming. The number of individuals was always higher at the reference sites than that of farm sites. Maximum number of individuals (1278 m^{-2}) was recorded at the first year farm site and the minimum (279 m^{-2}) at the fourth year farm site. Improvements in number of species, number of individuals were noticed at farm sites when crop holiday was given and a crop holiday of six months proved to be useful in rectifying the impact of oyster farming of two years. Based on findings of the present study it is recommended that oyster farming can be done continuously for a maximum period of two years and if the culture needs to be carried for more than two years at the same site, a crop holiday of at least six months is to be given. Alternately, the location of farming has to be shifted to an adjacent site after 2 years.

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1. INTRODUCTION

Historically, the oceans were considered limitless and thought to harbour enough fish to feed an ever increasing human population. However, the demands of a growing population, particularly in poorer countries, now far outstrip the sustainable yield of the seas. At the same time as fishing has become more industrialised and wild fish stocks increasingly depleted, aquaculture production – fish and shellfish farming – has grown rapidly to address the shortfalls in capture fisheries.

With the world population doubling in size from 3.6 billion people from 1960 to 1999 and currently growing at 1.33% per year, and expected to reach 7.3 to 10.7 billion by 2050 (with 8.9 billion considered most likely), there are growing doubts as to the long term sustainability of many traditional agricultural food production systems in being able to meet the increasing global demand for food. Nowhere is this more critical than within many of the world's developing countries, and in particular within those low income food deficit countries (LIFDCs) which are net importers of food and lack sufficient earnings to purchase food to cover their basic dietary needs. Of the multitude of agricultural food production systems, aquaculture is widely viewed as an important potential system capable of contributing to reductions in the shortfall in the terrestrial food basket. Also as an inexpensive source of a highly nutritious animal protein, aquaculture has become an important activity for improving food security, raising nutritional standards and alleviating poverty, particularly in the world's poorest countries.

According to FAO statistics, the contribution of aquaculture to global supplies of fish, crustaceans and molluscs continues to grow, increasing from 3.9 percent of total production by weight in 1970 to 43 percent in 2005. Aquaculture continues to grow more rapidly than all other animal food-producing sectors. Worldwide, the sector has grown at an average rate of 8.9 percent per year since 1970, compared with only 1.2 percent for capture fisheries and 2.8 percent for terrestrial farmed meat production systems over the same period. Production from aquaculture has greatly outpaced population growth, with the world average per capita supply from aquaculture increasing from 0.7 kg in 1970 to 6.4 kg in 2002, representing an average annual growth rate of 7.2 percent (FAO, 2004).

Since aquaculture cannot function in isolation it will have to interact with other sectoral / subsectoral components (agriculture, fishing, forestry, tourism, and other community activities) in the surrounding area. The increasing conflicts arising from the interaction among other sectoral components and utilisation of coastal resources for aquaculture development and the associated adverse impacts on the coastal environment have all raised doubts regarding the 'sustainability' of coastal aquaculture. The concerns raised relate to deficiencies in existing aquaculture legislation and planning methods, the use of certain farming practices, issues of resource use efficiency, disease treatment and control, environmental degradation, social welfare and employment opportunities etc.

Over the last few decades a considerable amount of scientific literature has been devoted to the environmental impacts associated with coastal aquaculture. The negative impacts have been associated mainly with high-input, high output intensive systems, the effects of which can include nutrient and organic enrichment of recipient waters resulting in buildup of anoxic sediments, changes in benthic communities and the eutrophication of lakes, degradation of wetlands, local water pollution and salination problems, misapplication of chemicals, collection of seed from wild, introduction of exotic species and overuse of fishery resources as feed inputs.

Mariculture is the rearing of the aquatic organisms under controlled or semi-controlled conditions in coastal and offshore waters in which the salinity is maximal and not subject to significant daily or seasonal variations. Apart from contributing to the production of protein rich food, mariculture has been the source of livelihood of several coastal villagers. Most aquaculture production comes from the freshwater environment (57.7 percent by quantity and 48.4 percent by value). Mariculture contributes 36.5 percent of production and 35.7 percent of the total value (FAO, 2004).

Although on a world-wide scale bivalve aquaculture is perhaps of less economic importance than finfish culture, in some countries like UK, France, Canada, Ireland and USA considerable areas of coastline are dedicated to either mid-water mussel culture or intertidal oyster and clam culture. In view of the large spatial scale of many intertidal bivalve aquaculture operations, the potential exists to induce large – scale changes in contrast to the usual smaller spatial scale of finfish operations.

The impact of bivalve culture, which is mostly due to mussel and oyster farms, is related to the intensive biodeposition of faeces and pseudo-faeces that modify the physical and chemical characteristics of the benthic environment as they accumulate in the bottom sediments. This phenomenon is well known and documented for intensive fin-fish aquaculture. However, the impact of bivalve farming is expected to be less relevant than fish farming, because in the latter the impact due to the accumulation of biodeposits is further increased by the accumulation of organic matter due to uneaten food. Nonetheless, a wide variety of negative effects have generally been reported for bivalve farming since biodeposition can induce severe organic matter accumulation and reducing conditions in the sediments beneath the bivalve growing structures. This in turn, affects benthic biodiversity and community structure, altering trophic interactions and pathways of energy transfer from bacteria to meiofauna and macrofauna.

In India, since the last decade considerable changes have taken place in diversification and production of mariculture, most significant of which is the emergence of oyster and mussel farming as a commercial aquaculture program and the production estimate in the year 2005 is 9000 tonnes which is more than the production from several other Asian countries like Bahrain, Hong Kong, Kuwait, Cyprus, Oman, Pakistan, and UAE making the nation the 16th in rank in Asia. The development of oyster farming as a small-scale industry has led to employment generation in coastal villages. Self-employment of villagers as owners of aqua farms and as part time workers in activities related to seed collection, seeding, heat shucking and marketing has led to economic empowerment of villagers especially women. Among the maritime states Kerala has well established commercial farms and there are more than 2000 villagers directly earning additional income every year through oyster farming

It is well known that known that large scale aquaculture can pose complex ecological, socio-economic and management problems. Hastings and Heinle, (1995) commented that "The potential for increased farming of coastal marine waters is considerable but the potential for significant environmental degradation associated with such activities is also large". The coastal waters of Kerala are now increasingly being put into use for bivalve mariculture activities, but there is no available

information on environmental impacts associated with bivalve mariculture specially related to oyster culture. The present study is aimed at this aspect and negative impacts if any associated with oyster culture are looked at with main intention of management interventions rather than to reject oyster culture as an unhealthy practice. This investigation is intended for to promote a healthy environment – preventing environmental degradation in such a way that the coastal ecosystem is able to sustain both aquaculture and the critical habitat of estuary dependent resources. The present work was undertaken with the following objectives.

- To quantify the impact of short term and continuous farming of oyster, *Crassostera madrasensis* (Preston) on hydrographic parameters
- To quantify the impact of short term and continuous farming of oyster, *Crassostera madrasensis* (Preston) on sediment characteristics
- To assess the benthic macrofaunal community changes due to the short term and continuous farming of oyster, *Crassostera madrasensis* (Preston)
- To assess the impact of giving crop holiday of three to nine months on improvements in hydrographic parameters, sediment characteristics and benthic macrofaunal communities after farming of oyster, *Crassostrea madrasensis* (Preston).

2. REVIEW OF LITERATURE

2.1 Overview of Impacts

2.1.1 Coastal Aquaculture

Over the last few decades considerable amount of scientific literature has been devoted to the environmental impacts associated with coastal aquaculture. This has been primarily driven by the increasing importance of aquaculture as an economic activity and potential conflicts arising from perceived negative impacts of suspended finfish culture. These usually take the form of modifications in the soft-sediment community structure in the vicinity of aquaculture sites (Gowen and Bradbury 1987; Wu *et al.*, 1994; Henderson and Ross 1995; Axler *et al.*, 1996; Kelly *et al.*, 1996; Read *et al.*, 2001a; Christensen *et al.*, 2003) or interactions of chemicals used on farms with the surrounding ecosystem (Pillay 1992)

Although on a world-wide scale bivalve aquaculture is perhaps of less economic importance than finfish culture, in some countries considerable areas of coastline are dedicated to either mid-water mussel culture or intertidal oyster and clam culture. In terms of benthic community modifications, some of the environmental effects of suspended bivalve culture are similar to those described for finfish farming (Mattson and Linden, 1983). In contrast, most studies on intertidal culture have either failed to demonstrate any significant changes in benthic community structure (Mojica and Nelson, 1993; Goncalves da Casta and Nalesso, 2006) or have only detected minor changes (Nugues *et al.*, 1996; Kaiser *et al.*, 1996; Spencer *et al.*, 1996). Nevertheless, in view of the large spatial scale of many intertidal bivalve aquaculture operations, the potential exists to induce large-scale changes (Nugues *et al.*, 1996), in contrast to the usual smaller spatial scale of finfish operations.

More recently aquaculture in marine waters has seen a dramatic increase, and concern about organic enrichment from this source, especially in coastal marine environments, has grown (Larson, 1985; Gowen and Bradbury, 1987; O'Connor *et al.*, 1989; Prakash, 1989; Silvert, 1992; Hargrave, 2003). Aquaculture impacts from shellfish and finfish culture may be distinguished in that the latter involves a net addition of organic matter in the form of fish feed to the environment (Folke and

Kautsky, 1989). Shellfish culture relies on natural sources of seston for food, and although there is no net addition of organic matter to the ecosystem, suspension feeders package phytoplankton and other seston into larger particles (feces and pseudofeces), which may cause locally increased deposition of material to the benthos (Kautsky and Evans, 1987). Previous studies of natural shellfish productions have demonstrated the ability of oyster reefs, mussel beds, and other dense aggregations of bivalves to regulate nutrient fluxes, sedimentation, and primary production in coastal ecosystems (Asmus and Asmus, 1991; Dame *et al.*, 1991). There are fewer studies in this regard, but it is clear that suspended culture can produce similar effects (Tenore *et al.*, 1982).

2.1.2 Bivalve Aquaculture

Though less important than finfish farming (Findlay *et al.*, 1995; Christensen *et al.*, 2003; Crawford *et al.*, 2003), bivalve culture activities are known to cause seabed disturbances. Through their feeding activities, mussels may alter the nutritive value, stability and textural composition of the sediments by removing large amounts of suspended material and altering sedimentation rate through biodeposits directly under the aquaculture operation sites (Tenore *et al.*, 1982; Hargrave, 1994; Kaiser *et al.*, 1998; Christensen *et al.*, 2003).

Studies carried out on the impact of shellfish farming on the benthic environment present various data sets that suggest a large spectre of effects ranging from small (Baudinet *et al.*, 1990; Buschmann *et al.*, 1996; Crawford *et al.*, 2003) to important (Dahlback and Gunnarson, 1981; Kroncke 1996; Tenore *et al.*, 1982; 1985, Mattson and Linden 1983; Kasper *et al.*, 1985; Grant *et al.*, 1995; Sorokin *et al.*, 1999; Stenton-Dozey *et al.*, 1999; Mirto *et al.*, 2000; Chamberlain *et al.*, 2001; Christensen *et al.*, 2003; Smith and Shackley; 2004). This wide range of impacts observed in the literature is largely related to various local effects such as the heterogeneity of the coastline (e.g.open versus protected), various oceanographic (e.g.currents, tides, flushing time) and biological parameters (e.g.overall productivity of the ecosystem, algal and animal communities) as well as husbandry practices. Details of environmental impacts of bivalve mariculture on the environment are given in reviews by Kaiser *et al.*, (1998) and Kaiser (2000).

2.2 Environmental Impacts

There is an increasing awareness of the environmental effects that may result from the various stages of bivalve cultivation processes. The environmental effects of aquaculture practices with respect to hypernutrification, inputs of chemicals and antibiotics, sedimentation and alteration of benthic communities have been studied extensively in recent years (Tenore *et al.*, 1982; Tenore *et al.*, 1985; Rodhouse *et al.*, 1985; Rodhouse and Roden, 1987; Gowen and Bradbury, 1987; Gowen *et al.*, 1989; Weston, 1990). The associated environmental effect of aquaculture may be localized (e.g. around salmon farms) (Brown *et al.*, 1987) or large scale (e.g. oyster culture in the Bay of Marennes-Oleron, France) (Heral *et al.*, 1986) depending upon the size and extent of the farming activity. The scientific assessment of environmental impacts of cultivation, however, has been made mainly with respect to mussel and/or salmon farming and the effects of the invasive process of harvesting and wild stocks of subtidal scallops, Pecten maximus (L.), (McDonald, 1993), intertidal cockles, Ceratoderma edule (Cotter *et al.*, 1993) of hard shell clams, *Mercenaria mercenaria L.*, (Peterson *et al.*, 1987). However, few studies have been devoted to the environmental effects associated with the inter-tidal cultivation of hatchery reared bivalves in trays i.e., oysters

Ecological impacts of bivalve aquaculture techniques may be substantial in terms of biodeposits, altered flow regimes, and disturbance of the substrate (Everett *et al.*, 1995); other reports indicate low environmental effects (Buschmann *et al.*, 1996, Crawford et al. 2003).

2.2.1 Impacts on Water Composition

Normally any change in water composition can only be detected immediately beside the farm due to dilution by the sea. Changes in water composition are mainly due to removal of suspended solids from the water and excretion of soluble waste products back into it. Natural populations of bivalves are known to control phytoplankton blooms, reduce total suspended solids through filter feeding (Cloern, 1982; Officer *et al.*, 1982; Hammer, 1996; Soto and Mena, 1999) and recycle and remove organic nutrients in the water column (Doering and Oviatt, 1986; Rice, 1999).

2.2.1.1 Control of Suspended Particles

Dense bivalve populations may exert a strong influence on suspended particulate matter (including phytoplankton, detritus, and some auto- and heterotrophic picoplankton and microzooplankton) in some coastal systems through their huge capacity to clear particles from the surrounding water (Dame, 1996). A strong indication that bivalve filter-feeders are able to control suspended particulate matter in some coastal systems comes from documented ecosystem changes that occurred after large biomass variations in natural and cultured bivalve populations. Population explosions of introduced bivalve species in San Francisco Bay and dramatic reductions in oyster populations in Chesapeake Bay have been implicated as the cause of large changes in phytoplankton biomass and production experienced in these systems (Nichols, 1985; Newell, 1988; Nichols *et al.*, 1990; Alpine and Cloern, 1992; Ulanowicz and Tuttle, 1992). Research on the whole-basin environmental effects of bivalve aquaculture in France and Japan indicate that intense bivalve culture in these regions led to changes in particulate food abundance and quality, resulting in large-scale growth reduction and high mortalities in the cultured bivalves (Héral *et al.*, 1986; Aoyama, 1989; Héral, 1993). Speculation that intense bivalve culture can affect coastal ecosystems by reducing excess phytoplankton associated with eutrophication have been supported by some laboratory and field observations, but have not been rigorously proven.

Research on *C. virginica* indicates that suspension feeding by oysters can reduce local concentrations of suspended solids, carbon, and chlorophyll *a* but increase ammonia and local deposition of fine-grained sediment and detritus (Dame 1976; Dame *et al.*, 1984, 1986, 1992; Nelson *et al.*, 2004). The removal of particulate matter through suspension feeding increases water clarity, which probably has a positive influence on the growth and abundance of seagrass and other benthic primary producers (Peterson & Heck 1999, Newell 2004, Newell & Koch 2004).

Oysters provide numerous economic and ecological benefits including commercial fisheries value (Breitburg *et al.*, 2000; Mallin *et al.*, 2000), habitat diversity (Posey *et al.*, 1999; Breitburg *et al.*, 2000), and erosion control (Meyer *et al.*, 1997). Additionally, filtering by oysters may improve water quality by reducing suspended sediment and nutrients in aquatic systems (Gerritsen *et al.*, 1994;

Brumbaugh *et al.*, 2000; Mann, 2000). Through active filtration, oysters remove suspended particles above 3 µm from the overlying water column, thus reducing the concentrations of suspended sediments, detritus, and particulate-bound nutrients in estuarine environments (Bayne and Hawkins, 1992; Gerritsen *et al.*, 1994; Brumbaugh *et al.*, 2000; Mann, 2000). Field studies have shown that *Crassostrea virginica* beds may reduce chlorophyll *a* concentrations in the overlying water column by more than 75% (Dame *et al.*, 1984)

Nelson *et al.* (2004) examined the effects of small-scale oyster additions on sediment loading, chlorophyll a, nutrient concentrations, and flow in small tidal creeks. Their study demonstrated that small oyster reefs established and maintained in some small tributary channels can reduce TSS and chlorophyll a concentrations and that the magnitude of the effect may vary over the course of the tidal cycle.

Newell (2004) reviewed ecosystem influences of natural and cultivated populations of suspension feeding bivalve molluscs. Suspension feeding bivalves serve to couple pelagic and benthic processes because they filter suspended particles from the water column and the undigested remains, ejected as mucus-bound feces and pseudofeces, sink to the sediment surface. This biodeposition can be extremely important in regulating water column processes where bivalves are abundant in coastal waters and in seasons when water temperatures are warm enough to promote active feeding. Bivalves under these conditions can exert "top down" grazer control on phytoplankton and the process reduce turbidity, thereby increasing the amount of light reaching the sediment surface. This has the effect of reducing the dominance of phytoplankton production and extending the depth to which ecologically important benthic plants, such as seagrasses and benthic microalgae, can grow.

The potential ecosystem effects of bivalve grazing support previous literature reports that populations of suspension feeding bivalves can exert top-down control on phytoplankton production in estuarine and coastal waters (blue mussels, Riemann *et al.*, 1988; Prins *et al.*, 1995; Pacific oysters, Souchu *et al.*, 2001; and non native bivalves in San Francisco Bay, Cloern, 1982; Officer *et al.*, 1982)

Conversely, some investigators contend that bivalves may not reduce phytoplankton levels appreciably. This is based on their observations of high rates of nitrogen excretion by bivalves, nitrogen regeneration to the water column from bivalve biodeposits, and either estimates or direct measures of higher primary production and phytoplankton biomass associated with bivalve grazing (Doering *et al.*, 1986; Prins and Smaal, 1990; Asmus and Asmus, 1991; Dames and Libes, 1993; Yamomuro and Koike, 1993). The nitrogen released directly by the bivalves and regenerated from their biodeposits comes not only from ingested phytoplankton but also from nonphytoplankton material, such as nitrogen rich bacteria and flagellates (Asmus and Asmus, 1991) that are readily captured and digested by bivalves (Bayne and Hawkins, 1992). The regenerated dissolved inorganic nitrogen will stimulate phytoplankton production, hence explaining the enhanced primary production observed in the vicinity of the bivalves.

2.2.1.2 Nutrients

Compared with intensive finfish culture, environmental concerns associated with bivalve mollusk culture are low and normally only occur where culture covers a large area, have very high stocking densities, or are not properly managed. Nutrients in the form of phytoplankton are filtered from the water column by the mollusks and a large proportion (42% N and 58% C) is excreted. The remaining nutrients are either removed completely from the system during harvest, consumed by scavengers/decomposers or released as solid waste products. Although bivalve mollusk culture is a net remover of nutrients from the ecosystem through harvesting of the product, there is a complex interaction with nitrogen cycling processes in coastal waters. Bivalve mollusk culture is not a net contributor of nutrients to the water column as there is no supplementary feeding. Studies have estimated that for each tonne of mussels produced, 32.5 kg carbon, 6.6 kg nitrogen and 0.5 kg phosphorous will be removed from the system (NCC, 1989).

Other recorded impacts of bivalve mollusk culture on water quality include modification of the nutrient cycle within coastal ecosystems (NCC, 1989; Rodhouse *et al.*, 1985; Kasper *et al.*, 1985) as carbon and nitrogen ingested as phytoplankton will be converted into other forms and concentrated near to the culture area.

The literature on the role of bivalve mollusks in estuarine ecosystems shows that they are an essential part of healthy estuaries around the world, where they fulfill an important role in the retention of phosphorous and nitrogen (Dame *et al.*, 1989; Gottlieb and Schweighofer, 1996; Lenihan, 1999). Studies have also suggested that benthic bivalves are important facilitators of regenerating inorganic nutrients (Doering *et al.*, 1986, 1987; Dame *et al.*, 1991; Dame and Libes, 1993). Recently, Souchu *et al.* (2001) found that oysters were not food-limited during the summer due to the regenerating primary production enhanced by benthic nutrient fluxes from oyster beds in Thau lagoon, located in southern France.

The consumption and deposition of suspended particulate matter by bivalves, as well as the excretion of dissolved nutrients, can play a significant role in controlling the amounts and forms of nitrogen in coastal systems and the rate of nitrogen cycling (Dame, 1996). This transformation and translocation of matter by bivalves appears to exert a controlling influence on nitrogen concentrations in some coastal regions (Dame *et al.*, 1991) and can provide a means of retaining nutrients in coastal areas, where they are recycled within detrital food chains, rather than being more rapidly exported (Jordan and Valiela, 1982). Benthic nutrient mineralization can increase at culture sites as a result of the increased organic matter sedimentation, greatly speeding up the rate of nitrogen cycling (Dahlback and Gunnarsson, 1981; Kaspar *et al.*, 1985; Feuillet-Girard *et al.*, 1988; Barranguet *et al.*, 1994; Grant *et al.*, 1995). The high flux of ammonia excreted from dense bivalve populations may have a major effect on phytoplankton production (Maestrini *et al.*, 1986; Dame, 1996) and may potentially contribute to more frequent algal blooms, including those of the domoic-acid-producing diatom *Pseudo-nitzschia multiseries* (Bates, 1998; Bates *et al.*, 1998). Aquaculture-induced changes in the relative concentrations of silica, phosphorus and nitrogen (e.g. Hatcher et al., 1994) may also favor the growth of other harmful phytoplankton classes (Smayda, 1990), but this has yet to be observed in nature. Bivalve aquaculture may also play a significant role in nutrient cycling in coastal systems, as nutrients stored in the cultured biomass are removed by farmers and the nutrients are no longer available to the marine food web. Kaspar *et al.* (1985) suggested that the harvesting of cultured mussels may lead to nitrogen depletion and increased nutrient limitation of primary production, but there is little direct evidence of environmental effects. The retention and remineralization of limiting nutrients in

coastal systems is necessary to sustain system productivity, but the potential impacts of bivalve cultures on coastal nutrient dynamics is poorly understood.

Sediments regulate the production (fluxes) and the standing stocks (concentrations) of nutrients in the water (Kasper *et al.*, 1985; Hammond *et al.*, 1985). Mazouni *et al.*, (1996) studied the nutrient and oxygen exchanges at the water - sediment interface in a shellfish farming lagoon (Thau, France). They measured fluxes of inorganic nutrients and oxygen over a period of one year at two stations; one located under a culture table, which is being subjected to intensive accumulation of organic matter and other located outside the area. The oxygen content in the overlying water was higher outside the culture areas than under the culture tables. However, for the two stations, the inorganic nitrogen contents of the water column (whatever the chemical form, i.e., nitrate-nitrites or ammonium) were similar. The dissolved inorganic phosphorous concentrations were also similar at the two stations.

Soychu *et al.* (2001) studied how bivalve aquaculture altered water column nutrient cycling in a poorly flushed lagoon in the Mediterranean. They reported that for all seasons, except when phytoplankton were growing most rapidly in summer, bivalve grazing controlled phytoplankton biomass. Consequently, for most of the year the regenerated NH_4^+ from the aquaculture farms was not used by phytoplankton for new production. Instead it became available to be oxidized to NO_3^- by pelagic nitrifying bacteria, hence explaining their observation of elevated NO_3^- in the water column within the shellfish aquaculture farms. It is likely that this NO_3^- will diffuse into the sediments where it will be subject to denitrification, hence leading to N removal from these coastal lagoons.

Pietros and Rice (2003) investigated the impacts of aquacultured oysters, *Crassostrea virginica* on water column nitrogen and sedimentation. Based on rates of ammonia excretion by oysters and observed steady states of ammonia and other forms of inorganic nitrogen in mesocosm tanks, they hypothesized that ammonia generated by oysters is taken up by rapidly regenerating phytoplankton in the water column. Nitrate, chlorophyll *a*, ammonia, particulate inorganic matter in the water column, particulate organic matter in the water column, total particulate organic matter on the bottom at the end, and total particulate inorganic matter on the bottom

at the end of experiment showed no significant differences between treatment tanks with oysters and the controls (Pietros and Rice, 2003).

Dentrification is stimulated in sediments beneath bivalve aquaculture operations, including New Zealand mussels (Kaspar *et al.*, 1985), and oysters in the south of France (Gilbert *et al.*, 1997). Recent evidence by Newell *et al.* (2002) have shown that *C. virginica* in shallow water may be increasing rates of denitrification by showing denitrification rates in sediment cores with added phytoplankton cell slurries as an experimental analog for oyster feces and pseudofeces.

Changes in water quality have been detected in water passing through a shellfish farm, with both ammonical nitrogen and inorganic phosphorous levels increasing (Meikle and Spencer, 1992). There are reports of large ranges of fluxes for many of the same nutrients both within the same study site and among sites; therefore, the impacts of shellfish culture can be difficult to quantify (Dame and Danker, 1988; Hatcher *et al.*, 1994).

On an annual basis oxygen and nitrate are mainly taken up by the sediment beneath the oyster beds, where as ammonia, urea and primary amines are released to the water column. Oysters' metabolic activities influence the intensity of these exchange rates by their own respiration and excretion. Soluble end products are released to the surrounding water and biodeposits modify the particulate input into the sediment.

2.2.2 Benthic Impacts

Benthic environmental impacts may arise from the deposition of solid wastes from the mollusks growing on the structures (longlines, raft/racks). Solid wastes from bivalve culture comprise organic faeces and pseudofaeces, shells and other detritus discarded or dislodged from the farm (NCC, 1989). The wastes that are deposited will fall through the water column and settle on the sediment beneath or near to the longlines. These wastes can potentially alter the physical character of the sediment; alter nutrient cycling in the sediment or cause biological changes to the macrobenthic community.

The impact on the benthic environment appears to be strictly dependent upon several factors, including:

(i). the culturing method

(ii). the density of cultivated organisms

(iii). the water depth

(iv). the hydrographical conditions in the area

(v). Age of the farm

(vi). Hydrodynamics and sediment adsorption etc

Farm management practices also play a role in determining impacts on the sediments. In areas with high densities of shellfish culture and low tidal flushing, this can lead to an accumulation (or concentration) of organic matter in the sediments and the enhancement of benthic fluxes of nutrients (Souchu *et al.*, 2001). Chamberlain, *et al.*, (2001) consider that one important factor determining the final fate of faecal matter, and any subsequent impact, is the dispersion of biodeposits from the farm site.

The impact of bivalve culturing, which is mostly due to mussel and oyster farms, is related to the intensive biodeposition of the faeces and pseudo-faeces that modify the physical and chemical characteristics of the benthic environment as they accumulate in the bottom sediments (Kasper *et al.*, 1985; Gilbert *et al.*, 1997; Mirto *et al.*, 1999a). This phenomenon is well known and documented for intensive fin-fish aquaculture. However, the impact of mussel farming is expected to be less relevant than fish farming, because in the latter the impact due to the accumulation of biodeposits is further increased by the accumulation of organic matter due to uneaten food (Mazzola *et al.*, 2000; Crawford *et al.*, 2003).

Nonetheless, a wide variety of negative effects have generally been reported for mussel farming since biodeposition can induce severe organic matter accumulation and reducing conditions in the sediments beneath the cages (Kasper *et al.*, 1985; Tenore *et al.*, 1985; Kaiser *et al.*, 1998; Mirto *et al.*, 2000). This in turn, affects benthic biodiversity and community structure, altering trophic interactions and pathways of energy transfer from bacteria and picoeukaryotes (Mirto *et al.*, 2000; Danovaro *et al.*, 2003) to meiofanuna (Dinet *et al.*, 1990; Mirto *et al.*, 2000); and macrofauna (Castel *et al.*, 1989; Stenton – Dozey *et al.*, 1999).

2.2.2.1 Biodeposition, Sedimentation and Nutrient Recycling

Biodeposition is the term given to the accumulation of faces and pseudofaeces under the shellfish farms. These biodeposits may represent a significant proportion of the energy potentially available to consumer invertebrates as a food resource. Nitrogen and phosphorous bound to phytoplankton and other forms of particulate matter are recycled back into the water column via biodeposition, thus reducing the immediate loss of nutrients to the sediments (Kautsky and Evans, 1987). Benthic filter feeders seem to serve as important agents in stimulating bacterial growth which provides the benthos with nutritious food (Kautsky and Evans, 1987). This may be due to the fact that biodeposits, as studied by Kautsky and Evans (1987) having a C/N ratio of about 8, and so may be classified as of high nutritional value. Dankers and Zuidema (1995) make the point that although more nutrients are available through biodeposition, it is not clear whether speeding up of nutrient cycles actually results in increased primary production.

The issue of most concern regarding biodeposition is the intense concentration over a limited area. Before cultivation zooplankton grazing occurs throughout the system and associated processes, such as excretion of ammonia and deposition of faecal deposits are widespread. By replacing zooplankton grazing with mussel grazing these processes will be concentrated rather than dispersed. This might be expected to alter the composition and distribution of benthic fauna (Rodhouse and Roden, 1987; Meikle and Spencer, 1992)

Mussel farming is known to be responsible for intensive biodepostion of faeces and pseudo-faeces that might cause strong changes in the physical and chemical characteristics of the sediments beneath the long lines (Dahlback and Gunnarsson, 1981; Gilbert *et al.*, 1997; Kaspar *et al.*, 1985; Mirto *et al.*, 1999b). The effects of mussel farms on benthic environments are likely to be of limited spatial extension and appear less relevant than those due to intensive fish farm activities (that employ external sources of organic matter, Mazzola *et al.*, 1999, 2000). The effects of biodeposits from suspended mussel culture on the local benthic environment have been considered in a number of studies (Tenore *et al.*, 1982; Kaspar *et al.*, 1985; Baudinet *et al.*, 1990; Hargrave, 1994). The reported effects on the physicochemical

and biological structure of the surrounding surficial sediments were generally similar, although the extent and degree of these differed considerably among locations.

Biodeposition affects the sediments and benthic communities to a degree that varies widely between sites and appears to be related to current velocity (Fischer, 1994). The most vulnerable areas are those with slow currents and shallow waters. Dahlback and Gunnarsson (1981) examined the environmental impacts of intense mussel farming in Sweden, where the currents are generally weak (3 cm/s). The sedimentation rate under the culture (3g $C/m^2/d$) was three times higher than at the nearby control site. Grenz (1989) suggested that average biodeposits in suspended culture could reach quantities up to 345 kg m^{-2} $year^{-1}$. In contrast, Kasper *et al.* (1985) working on water quality at a green lipped farm with current velocities up to 110 cm/s found no significant differences between inorganic and organic nitrogen, total and soluble reactive phosphorous, silicate, calcium and magnesium concentrations in the centre of the farm and at a control site. This is in agreement with Rodhouse *et al.* (1985) who reported well-dispersed biodeposits from the mussel rafts in Killary Harbour.

If biodeposits accumulate, this may result in increased oxygen consumption, anoxia and denitrification (Kasper *et al.*, 1985) as well as increased sulphate reduction (Dahlback and Gunnarsson, 1981). The sediments under mussel farms will become enriched with carbon, nitrogen and phosphorous (to a lesser extent). This enrichment has been reported to change the characteristics of the sediment under farms (Dahlback and Gunnarsson, 1981; Kasper *et al.*, 1985). They found that the sediment under mussel cultures had a finer texture, lower bulk density and higher water content than those at adjacent stations. Mattson and Linden (1983) also found sediments under mussel farms to be slightly finer and in addition noted that they had a higher organic content and a negative redox potential when compared to reference sites.

As a result of biodeposition the oxygen consumption of heterotrophic organisms in the sediments will increase. Jorgensen (1980) reported that mussel beds in Denmark increase the benthic respiration per m^2 ten fold and thereby enhance oxygen depletion of the bottom water. When the oxygen demand exceeds the available oxygen then the redox potential decreases and the sediments become

anoxic (Meikle and Spencer, 1992). As the sediments become anoxic a build up and release of hydrogen suphide, ammonium and methane may result (Dahlback and Gunnerson, 1981). Hatcher *et al.* (1994) measured concentrations of 10 ppm of hydrogen sulphide at the mussel line site 6 cm below the sediment surface, rising to 196 ppm at 44 cm depth. In contrast, reference site concentrations of hydrogen sulphide were not measurable until a depth of 30 cm (2 ppm) which rose to 41 ppm at 40 cm depth. In this situation outgassing of hydrogen sulphide can happen. If this happens local populations of fish or other organisms may be adversely affected, although there is no evidence of it causing harm to mussels. In well oxygenated waters hydrogen sulphate is rapidly converted to harmless sulphate and therefore if a farm is located in well flushed waters anoxia and outgassing should not be a problem.

Sedimentation beneath the farms will also be due to the presence of artificial structures within the water body which provides an impediment to the flow (Kirby, 1994b). Anything which slows the flow of water will cause it to drop part of its sediment load therefore increasing the amount of sedimentation. The same principle will apply to trestles, cages, longlines and rafts.

Biodeposits are made up of faeces and psedofaeces and fall onto the sediment below the trestles. These pseudofaeces consist of mineral components that the Pacific oyster rejects while sorting the seston. The faeces consist of the organic matter which went through the digestive tract. The distance of 0.5 m between the trestles and the sediment may allow sufficient water movement to remove any biodeposits which may fall to the sea floor (Razet *et al.*, 1990).

Biodeposition from pseudofecal and fecal production by *C. gigas* and the resulting chemical changes in both sediment and the overlying water column have been extensively studied (Deslous-Paoli *et al* 1987, 1992, Sornin *et al* 1983). Nugues *et al.* (1996) noted an increase in organic and silt composition sediment beneath the trestles. In this case water velocity was noticeably decreased by the presence of trestles which probably lead to the increase in sedimentation rate observed beneath them. Cho *et al.* (1982) found great quantities of organic matter and sulphides in the bottom mud of shellfish (unidentified species) in the innermost part of Jinhae Bay, Korea. There were mainly due to excrements from shellfish and

fouling organisms. Other studies have shown that trestle cultivation of oysters is responsible for increased sedimentation of both organic matter and contaminants (Martin *et al.*, 1991; Kirby, 1994b). Sornin *et al.* (1983) went as far as to say that the accumulation of biodeposits by oysters brings about noticeable geological modifications of the underlying sediment. He recorded an increase in the organic, silt and phaeopigment content beneath the trestles which was again probably related to the recorded decrease in current velocity at both sites (Sornin *et al.*, 1983). They recorded daily deposits of 8-99 grams of carbon a square meter from directly beneath the oyster tables (Sornin *et al.*, 1983).

Martin *et al.* (1991) looked at the significance of oyster biodeposition in concentrating organic matter and contaminants in the sediments. The results showed that biodeposition leads to sedimentation of matter which can reach 700 $g.m^{-2}.J^{-1}$ and 500 $g.m^{-2}.J^{-1}$ on a sandy shore and in a clay bottomed pond respectively. Sedimentation results in organic matter and chemical contaminants accumulating on the seabed. The impact was particularly noticeable in the sandy sediment, and was observed down to a depth of 25 cm. This accumulation was not irreversible. Due to the washing of sand, the vertical profiles of organic matter and contaminants in the foreshore sediment became similar to those observed in the reference sediment two months after stopping the oyster rearing and so the biodepositon. In contrast, Cho and Park (1983) looked at eutrophication of bottom mud in Goseong – Jaran Bay, Korea, an off-bottom oyster and arkshell fishery and found no change in status since 1976.

The presence of trestles has been noted to decrease water velocity causing increased sedimentation (Nugues *et al.*, 1996). Their presence may have the effect of causing the water body to slow down and deposit more of its sediment load. This is certainly the case for intertidal oyster and mussel farms in France where about 30% face problems of sedimentation. This problem forces occasional relocation and abandonment of the beds (Weston, 1990). Kirby (1994b) discusses ways in which the presence of trestles can result in increased sedimentation have a negative affect on the farm itself, with records of whole oyster farms being destroyed by smothering (Kirby, 1994b). At high densities, *C. gigas* generates biodeposits, which leads to reduced particle size and increased organic content in sediment (Castel *et al.* 1989),

impacts that are avoided at lower oyster densities or higher flow rates (Crawford *et al.* 2003). The productivity of densely-stocked Japanese oyster grounds was detrimentally affected by the generation of large quantities of pseudofaeces and high filtration rates (Ito and Imai, 1955; Kusuki, 1977). Pseudofaeces production was so great beneath oyster cultivation rafts that it was at least equivalent to natural sources of sedimentation (Mariojouls and Kusuki, 1987).

The effects of shellfish farming on the benthic environment were investigated at three long-established subtidal oyster and mussel farms that had had relatively high levels of production (averaging 20 tonnes/ha per annum) and at control sites (Crawford *et al.*, 2001a). The results overall indicated little effect of shellfish farming within the lease, and no impacts outside the lease boundary. Redox, organic carbon, sulphide levels and rates of deposition were not significantly different between outside and inside each farm, although they were different between farms. A qualitative assessment (video recordings) of the risks of ecological impact occurring as a result of shellfish farming activities also suggested a low risk of impact due to accumulation of organic wastes from the farms (Crawford, 2001).

Crawford *et al.* (2003) investigated the benthic environment under and near three shellfish farms in Tasmania, Australia, which had had a relatively high level of production. The results suggest that the effects of shellfish (mussels and oysters) farming activities on the benthic environment under and near subtidal shellfish farms were low, and far less than results obtained from similar research conducted around salmon farms in Tasmania (Crawford *et al.* 2001, 2002). In contrast to conditions observed under some salmon farms, no extensive mats of Beggiatoa bacteria or spontaneous outgassing were observed, and the redox values did not drop below zero.

Danovaro, *et al.*, (2004) investigated the impact of a large mussel farm on the benthic environment using a battery of benthic indicators of environmental quality (including biochemical, microbial and meiofaunal parameters). No effects are seen in terms of sediment oxygen penetration and the downward fluxes (as the total mass, organic and pheopigment fluxes). The indicators based on the biochemical compositions of the sediment organic matter and microbial parameters also show no evidence of the eutrophication process, except as a slight increase in the bacterial

density in the sediments beneath the long-lines of the farm during the period of highest mussel stocks. Danovaro *et al.* (2004) were of the view that mussel farming in the investigated system was eco-sustainable and did not significantly alter the coastal marine ecosystem, both in terms of the functioning and tropic state.

The ecosystem effects of an increase in bivalves on sediment nutrient regeneration, and hence on phytoplankton production, will vary depending on bivalve population density and the rate of mixing of oxygenated water down to the sediment surface. Excess biodeposition, especially in low water flow environments, has the potential to stimulate bacterial respiration to such an extent that the sediments become anoxic, thereby inhibiting coupled nitrification – denitrification and causing sediment-bound P to be mobilized. Such local adverse effects can be ameliorated by moderated water currents or wave action that allows biodeposits to be spread across a larger bottom area and that mix oxygen from the surface to the bottom waters (Haven & Morales – Alamol, 1968; Dame *et al*, 1991).

The adverse effects of sediment overenrichment by bivalve biodeposits have often been observed in sediments underlying bivalves in suspended raft culture. For example, Ito and Imai (1955) reported that intensive oyster aquaculture resulted in underlying sediments becoming anoxic, and these effects appeared cumulative because the longer oysters were cultivated in a location, the more frequently sediment anoxia occurred. Such reductions in sediment oxygen content will reduce rates of bacterially mediated nitrification and increase the proportion of N released NH_4^-. When sediments become completely anoxic, the build up of H_2S can kill the aerobic nitrifying bacterial community. Consequently, even if aerobic conditions in the surface sediments are restored, nitrification will only recommence following the regeneration of the nitrifying bacterial community (Henriksen & Kemp, 1988, Sloth *et al.* 1995). Tuttle and Jonas (1992) also observed elevated amounts of microbially labile organic matter in surficial sediments beneath eastern oysters grown in floats in Chesapeake Bay. This led to about a 4 fold increase in sulfate reduction rates, although this increase was short-lived and confined to sediments in the immediate vicinity of the floats. These findings suggest that extremely dense bivalve communities can adversely affect sediment microbial processes by shifting them form

aerobic to anaerobic metabolism as result of increased particulate organic matter loading.

2.2.2.2 Biodeposition and the Benthos

Biodeposition by bivalves generally provides a strong input of organic matter of high quality and availability to benthic assemblages. Organic loading in the marine environment usually involves an increase in sediment oxygen demand by benthic microorganisms and fauna, and subsequent depletion of oxygen in porewater and near bottom water (Pearson and Rosenberg, 1978). The hypoxic sediments characteristic of organic enrichment are a haven for opportunistic or pioneer species such as the polychaete Capitella capitata, which are small, short lived, prolific, and capable exploiting suboptimal environments. At the other end of the spectrum are equilibrium species such as various large bioturbators, which tend to be long-lived, iteroparous, and exert a substantial effect on sediment chemistry via pumping, burrowing, and feeding activities. The equilibrium species occur as a successional end member away from the disturbance in either space or time (Rhoads *et al.*, 1978).

Modifications to the soft-sediment communities found in the vicinity of suspended finfish or bivalve cultivation have been extensively documented (Tenore *et al.*, 1982; Rodhouse *et al.*, 1985; Rodhouse and Roden, 1987; Gowen and Bradbury, 1987; Gowen *et al.*, 1989; Henderson and Ross, 1995; Hargrave *et al.*, 1993, 1997; Duplisea and Hargrave, 1996; Burd 1997; Ervik *et al.*, 1997; Read *et al.*, 2001). The area of seabed affected by inputs from these cultivation practices is usually restricted to immediately beneath or adjacent to the cultivation area (Mattson and Linden, 1983; Gowen *et al.*, 1989). Surprisingly few studies have examined environmental changes resulting from intertidal bivalve cultivation practices (Castel *et al.*, 1989).

Organic enrichment of the sediment directly under the bivalve culture is likely to have an additional local impact on the biomass and biodiversity. The impact on a particular site will depend on the type of sediment, current velocity and the species present.

Very few studies have been carried out on benthic community changes associated with intertidal oyster (*Crassostrea gigas*) culture. Castel *et a.l* (1989) provide summarized information on total abundance and biomass changes at two intertidal sites in Arcachon, France, one site having trestle-type cultivation and the other having 'parc' culture on the seabed. Nugues *et al.* (1996) studied benthic community changes in more detail at one site (trestle-type cultivation in the River Exe, UK. Summarized information on environmental impacts of large-scale bottom – type cultivation in Washington and Oregon (USA) is found in Simenstad and Fresh (1995).

Pocklington *et al.* (1994) looked at the polychaete response to different aquaculture activities a several sites in Canada. The polychaetes which dominated the fauna beneath the mussel lines were different from those beneath the fish cages. In both sites the sediments beneath the shellfish lines were black, finely pelleted and had high organic content with *Nephtys neoten* the dominant macrofaunal organism. Increased benthic microbial activity will often result in oxygen depletion and low macrofauna diversity as shown by Mattson and Linden (1983) and Kasper *et al.* (1985). According to FAO (1992), depletion of dissolved oxygen in the interstitial waters of organically enriched sediments results in the mortality or emigration of most species characteristic of undisturbed sediments. In addition, changes in algal (epibenthic as well as planktonic) production and/or species composition may result if the ratio of nitrogen to phosphorous is altered by the presence of mussel-lines.

Decreases in macrofaunal abundance have been detected in areas of extensive intertidal oyster cultivation (Heral *et al.*, 1986; Castel *et al.*, 1989). If there is organic enrichment of the sediment then there is likely to be some detectable change in the fauna. Nugues *et al.* (1996) noted small, but significant, changes in the macrofauna commuity sampled beneath oyster trestles, compared with that found in adjacent uncultivated areas. These changes were associated with an increase in organic and silt composition and a reduction in the depth of the oxygenated layer of the sediment beneath the trestles. They also noted that the main factors affecting the macrofaunal communities appeared to be linked to environmental parameters such as sedimentation rate and current velocity. In general the macrofaunal communities found in both the control and cultivated areas were impoverished and the abundance

of dominant species and diversity were low. The main differences between the fauna beneath the control and the two test sites was the decreased number of spionid underneath the trestles which may have been due to increased sedimentation.

Castel *et al.* (1989) investigated the influence of oyster (*Crassostrea gigas*) parks on the abundance and biomass patterns of meio- and macrobenthos in tidal flats. Oyster parks are intertidal layings of oysters surrounded by a fence to protect them from crabs and starfish. Castel found that when compared to the adjacent sandbanks, oysters clearly enhanced meiofaunal abundance (from 1130 to 4170 individuals 10 cm^{-2} but depressed macrofaunal densities (from 640 to 370 individuals 10 cm^{-2}). The organic rich oyster deposits probably favour meiofauna by increasing the trophic resources but do not favour macrofauna by inducing low oxygen concentrations. Moreover macrofauna are more sensitive to predation than meiofauna, probably due to size. Although *Crassostrea gigas* is a suspension feeder it does promote meiofaunal abundance. This points to the strong influence of biodeposits on structure and trophic resources available for meiofauna.

Dinet *et al.* (1990) studied bivalve aquaculture sites and observed that as biodeposition by *Crassostrea gigas* and *Mytilus edulis* increased, there was a commensurate decline in meiofaunal populations associated with sediment anoxia and elevated NH_4^+ in sediment pore water. Declines have also been observed (Tenore *et al.*, 1982, Rodhouse and Roden, 1987) in the abundance and species diversity of the burrowing and deposit-feeding macrobenthic organisms (bioturbators) that actively mix surficial sediments as a result of their feeding and burrow irrigation activity. Dinet *et al.*, 1990 demonstrated a strong impact of bivalve biodeposition on meiofauna density, which decreased dramatically (by a factor of four) when compared to the control site. Similar results were reported by Mirto *et al.*, 2000. Conversely, other authors reported an increase of the total meiofaunal density induced by mussel biodeposition (Castel *et al.*, 1989; Guelorget *et al.*, 1994; Radziejewska, 1986). However, a more detailed analysis revealed that such a positive response was observed in high energy environments (such as coastal lagoons), where resuspension events reduced organic matter accumulation and enhanced oxygen penetration into the sediments (Mirto *et al.*, 2000).

Moore (1996) looked at the impact of an intertidal oyster farm on the benthos in Dungarvan Harbour. She compared the benthos at the control site to that at the site with the oyster trestles (under the trestles and in the servicing lane between trestles). According to Shannon-Weiner index the fauna beneath the trestle was found to be less diverse that the control but surprisingly when Moore looked at fauna in the lanes between trestles she found that it was more diverse than control. She noted that the polychaete *Capitella capitata* was absent at the controls site but present in the lane and trestle site. This is an opportunistic species and perhaps colonized the lane and trestle treatment site possibly because of increased food resources. Usually *C.capitata* is an indicator of organic enrichment (Dahlack and Gunnarsson, 1981) but at much higher densities than found in this study. Moore also made the point that *C.capitata* is classified by benthic ecologists as an indicator of disturbed habitats. *Nephtys hombergi* and *Tellina tenuis* occurred at higher densities at the control site than at the oyster farm. Moore suggested that differences in all three species may be due to mechanical disturbance rather than organic enrichment.

Sammy De Grave *et al.* (1998) studied the changes in benthic macrofauna associated with intertidal oyster *Crassostrea gigas* (Thunberg) culture and the results did not indicate that the benthic community structure at the site below oyster trestles is undergoing any form of organic enrichment , as neither elevated levels of organic enrichment were encountered nor were potential organic enrichment indicator species, such as *Capitella capitata* encountered in densities usually associated with organic enrichment (Pearson and Rosenberg 1978).

Sylvand *et al.* (2004) investigated the impact of oyster farming on sedimentary cover and associated benthic macrofauna in an estuarine tidal flat: baie des veys, western France. An increasing of sediment mud content associated with oyster farming zone was noticed. The annelid *Scoloplos armiger* completely disappeared from the centre of the oyster culture area.

Mechanical disturbance may be due to the movement of tractors for service and maintenance. This can also lead to compression and churning up of sediments in the intertidal zone with negative effects on the invertebrate fauna (O'Brian, 1993). If plants, such as Zostrea, are present on the foreshore, they could also be damaged by tractor activities.

Other methods of oyster culture can cause disturbance to the benthos. In Washington, USA, Pacific oysters are grown in fenced off areas, known as parks, on the ground (Simenstad and Fresh, 1995). This regime is harsh on the benthic organisms as the growers may move the oysters several times to improve their growth. Harvesting is carried out with mechanical dredges and a plot may be harrowed, dredged, raked, leveled and treated with an insecticide carbaryl to destroy burrowing shrimp several times a year. In some cases seagrass is removed to increase water flow over the plots. Moreover, activities on the most intensively cultivated intertidal plots have been repeated annually for decades. These activities impose some level of disturbance on the benthic substrate and associated community (Simenstad and Fresh 1995). This method of culturing oysters appears to cause far more environmental damage than the current trestle based method.

2.3 Other Known Impacts

Effects of oyster culture (primarily dredging) were studied in 1962 and 1963 by Waddell (1964) in Arcata Bay, a part of Humboldt Bay in northern California. Comparing paired plots (one cultured plot and one uncultured), he concluded that the oyster culture impacted eelgrass shoot density, plant size (i.e. shoot length), and biomass. Impacts depended on the length of time each area had been cultured, with effects increasing as the length of time the plot had been under culture increased.

The disturbance of eelgrass habitats may not be confined to ground culture methods for oysters. Carleton *et al.* (1991) and Pregnall (1993) documented modifications or significant reductions in eelgrass habitat and biota as result of stake and rack culture in the South Slough National Estuarine Research Reserve, Coos Bay, Oregon, Carleton *et al.* (1991) found at least a 75% reduction in eelgrass shoots commensurate with decreased recruitment and survivorship of tellinid clams where stake and rack cultured oysters were harvested manually. Pregnall (1993) found almost an equivalent reduction in eelgrass shoots in an area of stake culture, associated with significant reductions in the densities of Dungeness crab (Cancer magister), macrofauna burrows, total infauna species, and small individuals of the bivalve *Cryptomya californica*.

The increased coupling of planktonic and benthic food webs by cultured bivalves has the potential to change energy flow patterns in coastal ecosystems, including altering food availability to zooplankton and larval fish (Horsted *et al.*, 1988; Newell, 1988; Doering *et al.*, 1989). Bivalve filter-feeders have a competitive advantage over zooplankton for food resources because they are able to respond immediately to increased food availability, while zooplankton must go through a complete life cycle before being able to fully exploit increased food resources. Direct ingestion of zooplankton by bivalves may also reduce zooplankton abundance (Horsted *et al.*, 1988; Davenport *et al.*, 2000). However, effects of bivalve culture on zooplankton communities are largely speculative owing to the limited research conducted.

Infectious diseases associated with intense bivalve culture, as well as exposure of cultured organisms to 'exotic' pathogens introduced with seed or broodstock, can have a significant and perhaps more permanent impact on ecosystems than the direct impact of the bivalves themselves (ICES 1995; Bower and McGladdery 1996; Hine 1996; Renault 1996; Minchin 1999; Miyazaki *et al.*, 1999). Bivalve neoplasias show strong correlations to heavily contaminated environments (Elston *et al.*, 1992), and the severity of infection is related to sub-optimal growing conditions (Elston 1989). Bivalve cultivation sites located in close proximity to sites of nature conservation interest, where environmental changes due to anthropogenic activities are viewed undesirable leading to a conflict of interest between conservation groups and bivalve growers (Dickson *et al.*, 1990; Vincent, 1992). Some "environmental" concern about shellfish farms has arisen due to user conflicts: opposition to shellfish farms from waterside landowners who find that farms spoil the view, and from commercial fishermen, sport anglers and recreational boaters who find their use of waterways hampered by culture structures (Lutz, 1980; Elliott and Hoagland, 1998).

2.4 Positive Impacts

The bivalve culture infrastructure provides new habitat and food chains, on a seasonal basis, for many forms of marine life. Polychaetes and crustaceans in particular are known to thrive in these habitats, which in turn provide valuable food source for marine fish. Dense assemblages of bivalves do not always cause adverse

changes in benthic community structure. For example, Dittmann, (1990) reported that biodeposition from beds of blue mussels leads to an enhanced and more diverse benthic invertebrate assemblage that will promote bioturbation.

The cultivation of bivalves can be a method of alleviating adverse environmental impacts arising from other activities in the coastal zone. For example, intensive fish farming has undesirable environmental impacts, particularly as the effluents are highly nutrient enriched, promoting the development of microalgal populations, some of which are toxic. It has been proposed that integrated fish/bivalve mariculture systems could ameliorate problems associated with algal blooms, as the bivalves would reduce algal densities and nutrients, which are effectively removed when the bivalve product is harvested (Folke and Kautsky, 1989; Shpigel *et al.*, 1993).

2.5 Summary of Environmental Impacts

The available literature has shown that extensive bivalve culture has the potential, under certain conditions, to cause cascading effects through estuarine and coastal foodwebs, altering habitat structure, species composition at various trophic levels, energy flow and nutrient cycling.

2.6 Research work carried out on oysters in India

In India, the first attempt to bring together the available information on oyster resources was made by Alagarswami and Narasimham, (1973) followed by Rao, (1974). The Central Marine Fisheries Research Institute brought out a comprehensive account on oyster resources, biology and culture in a bulletin entitled 'Oyster culture: Status and Prospects' (CMFRI, 1987). Rao *et al.* (1992) desribed the technology of seed production and farming of *Crassostrea madrasensis* and James and Narasimham, (1993) gave an account on oyster culture in a handbook on farming of Molluscs in India. Narasimham *et al.* (1993) gave an overview of the molluscan resources of the country which included oysters.

Recently Appukuttan *et al.* (2000) gave an update account of oyster culture along with the mariculture of other bivalves in the country while Muthaiah *et al.* (2004) gave information on oyster culture. Kripa *et al.* (2004) described the development

program in Kerala especially as a group farming activity. However the studies on environmental impacts of oyster culture are not attempted so far in India and this investigation is perhaps first one in this direction.

Table 1 Potential Environmental Impacts of Bivalve Culture (FAO/NACA. 1995; NCC, 1989)

Resource	Source	Impact	Potential consequences
Sediments	Metabolic wastes (pseudo faeces)	Accumulation beneath the culture sites	Localised deterioration in environmental quality
	Dead shells and other detritus	Accumulation beneath the culture sites	Alteration of physical structure of the sediment
Water column	Filter feeding of stock	Uptake of primary and secondary production	Positive impact on coastal eutrophication
			Depletion of essential nutrients
			Modification of nutrient cycle
			Reduction in dissolved oxygen levels
Biological	Seed stock	Collection of wild seed	Impacts on native population?
			Possible competition for feed
	Stock	Impacts on seagrass beds	Positive impact on biodiversity
			Potential impacts on whales and dolphins
	Subsurface infrastructure	Habitat creation	Increase in wild native shellfish population
	Cage infrastructure	Obstruction of native fauna	
	Stock	Creation of shellfish beds	
Coastal resources	Culture infrastructure	Large areas may interfere with the direction and velocity of tidal currents	Changes in sedimentation patterns
		Navigation	
			Social conflict
Amenity value	Culture infrastructure	Untidy or badly marked	Loss of visual amenity
	Servicing sites, processing	Noise, water quality impacts	Loss of amenity

Table 2 Postulated and documented local – scale effects associated with shellfish aquaculture

Nature of direct impact	Possible consequences	References
Nutrient enhancement through shellfish excretion	Enhanced algal growth rates	Gibbs et al., 1992
Nutrient release from degrading faeces & pseudofaeces	Buffering of pelagic nutrient depletion Enhanced algal growth rates	Tenore et al. 1982
Oxygen depletion within water column or sediments	Physiological stress amongst planktonic organisms, emigration or larger organisms Pulsed release of nutrients and sulfides etc from sediments	Considered unlikely in shellfish aquaculture operations (Morrisey & Swales 1996)
Change in particle size-spectra and particulate content in water-column	Changed sedimentation & Sediment characteristics Changed light scattering	Impacts upon light field considered unlikely (Ross, 2002)
Removal of phytoplankton	Reduced food supplies for other phtyo-herbivores Community composition biased towards fast-growing species	Gibbs et al. 1992; Olive et al. 2000) Dahlback & Gunnarsson, 1981
Release of larval shellfish into water column	Enhanced food supply for some planktivores Other phytoplankton may suffer greater competition for resources	Postulated
Depletion of zooplankton and eggs/larvae of fish & benthic invertebrates etc	Other organisms may suffer greater competition for resources	Tenore et al. 1985 Horsted et al. 1988)
Accumulation of organic detritus and shell hash on sea-floor	Oxygen depletion Nutrient release, Changed in benthic species assemblage	Dahlback & Gunnarsson 1981 Grenz et al. 1990 Kasper et al. 1985
Complexity contributed by the physical structure of the aquaculture facility and its biota	Changed species assemblage within the water - column and on the sea-floor (invasive species) changed hydrodynamics changed erosion/sedimentation characteristics	New Zealand experience with the ascidian Ciona intestinalis, Seaweed Undaria pinnatfida and other mussels Mytilus galloprovincialis

3. MATERIALS AND METHODS

3.1. Description of the species

Studies were carried on Indian backwater oyster *Crassostrea madrasensis* (Preston), which is the mainstay of oyster fisheries of India. Dense populations of this species are found along the coasts of Kerala, Karnataka and Maharashtra along the west coast of India and along Tamil Nadu, Andhra Pradesh and Orissa on the East coast. It inhabits backwaters, creeks, bays and lagoons from intertidal region to 17 m depth (Narasimham et al., 1993) (Plate 1a).

3.2 Description of the study area

Experiments were carried out in the Ashtamudi lake, which is the second largest estuarine system in Kerala lying between latitude 8^0 53' N and 9^0 02' N and longitude 76^0 31' E and 76^0 41' E with a water spread area of 44.73 square kilometers. Ashtamudi is the central portion of the vast expanse of the backwaters of Quilon region forming a very important fishing zone for various finfish and shellfish species of commercial importance. The estuary has a depth range of 1.83 m to 3.14 m with an average of 2.44 m (Nair et al. 1984; Nair and Azis, 1987)

3.3 Experimental Farms and Sampling

The impact due to oyster farming was assessed by studying the hydrographic parameters and sediment characteristics; and benthic macrofaunal community variations in the oyster farms constructed at Ashtamudi Lake, Kollam (Fig. 1).

3.3.1 Farm Sites under Farming Period

One fresh farm was constructed and the impact due to farming in the first (F1) and second year (F2) of farming was studied at this site, the former for a period of 9 months from January to September 2002 and the latter for 11 months from October 2002 to August 2003 (Plate 2b).

The impact due to farming for 3, 4 and 5 years of farming was studied at the CMFRI demonstration farm site in Ashtamudi Lake where oyster farming has been in practice for the past two consecutive years. The samples from CMFRI farm, which

represented the third year farm (F3), were collected for 2 months from January 2002 to February 2002 and this represented a full grown crop which was previously stocked in April 2001 by the CMFRI staff. After harvesting these rens by the end of February, new rens were placed in March 2002 and these were farmed till August 2002 and this represented the fourth year farm, F4 (Plate 1b). At the same site after harvesting the crop by the end of August, fresh rens were stocked in December 2002 and farmed till May 2003 representing farm F5. This stock was harvested during first week of June 2003 (Plate 3a & 3b).

3.3.2 Farm Sites under Crop Holiday Period

The changes in the ecosystem at the farm site after the oyster crop is harvested were also assessed. The changes during a crop holiday period of three (CH1) and nine (CH3) month's period were assessed at the farm site, F4 and F5 after the fourth and fifth year's crop was harvested (Plate 3a & 3b). The changes during a crop holiday period of six months (CH2) were assessed at the site of F2. The assessment period for crop holiday of three (CH1), six (CH2) and nine (CH3) months was from September to November 2003, from September 2003 to February 2004 and from June 2003 to February 2004 respectively. The experimental details regarding the farm sites, period of sampling and the stock-harvest details are summarized in the Table 3.

3.3.3 Reference Sites

The reference sites were located at approximately 100 m down side of the experimental farm sites in the same estuary.

3.4 Construction of oyster farm

Each experimental oyster farm of 5 x 5 sqm wooden structure (Plate 2b) was constructed using bamboo poles as described by Velayudhan *et al.* (1995). The stocking density was 500 rens per farm in all experimental farms. For preparing rens, the empty oyster shells were washed to remove silt and the foulers were scarped off. The shells after cleaning were dried and strung by drilling a hole in the center. Each ren consisted of five shells strung on a 3mm dia nylon rope at 10 to 15 cm interval (Plate 2a).

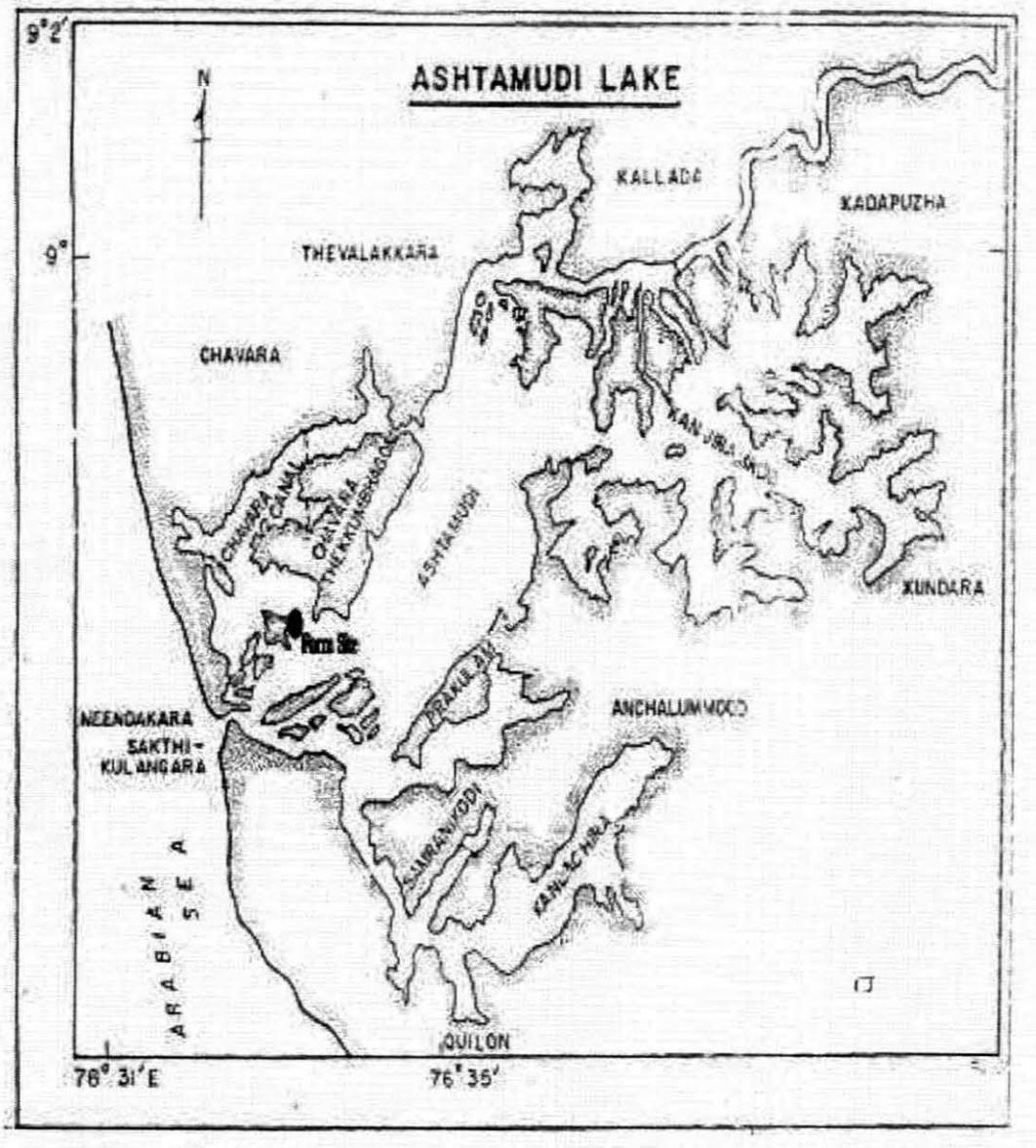

Figure 1 Map of Ashatamudi Lake showing the location of farms studied

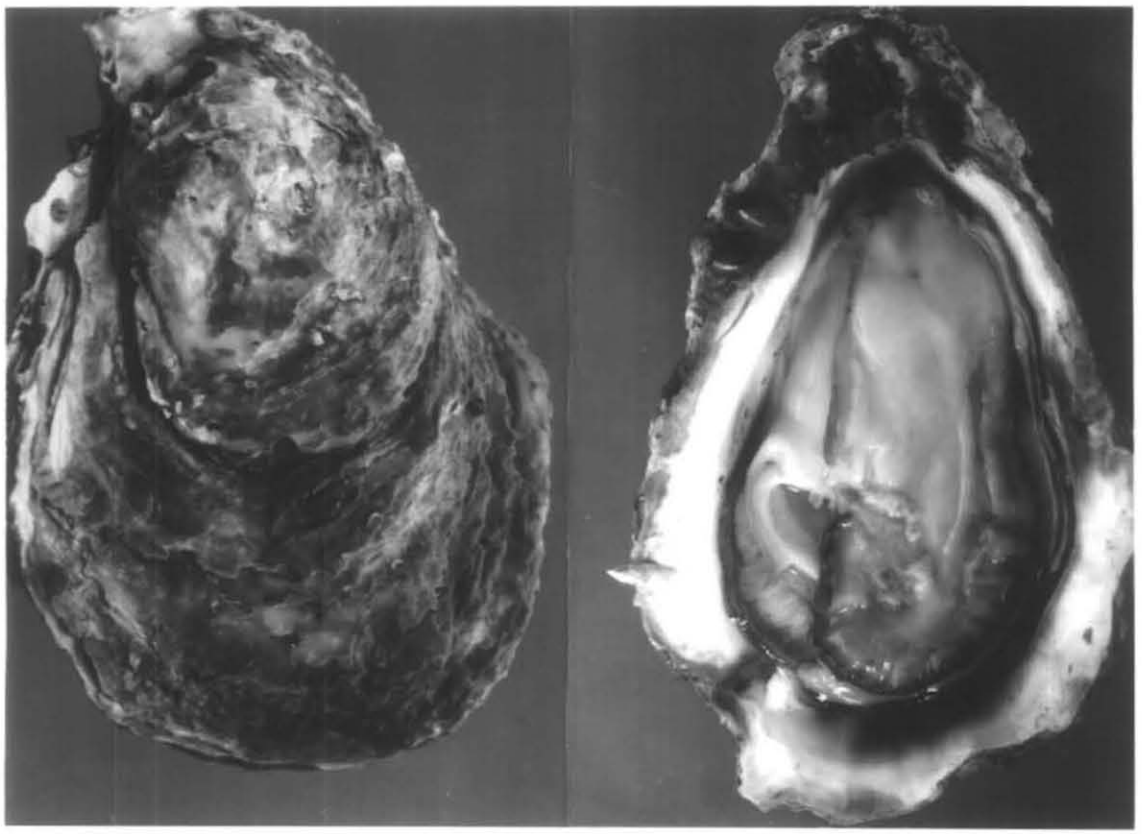

Plate 1a. Experimental oyster species studied, *Crassostrea madrasensis* **(Preston)**

Plate 1b. Experimental oyster farm used for studying impacts of 3rd, 4th and 5th year of farming.

Plate 2a. Ren made out of dead oyster shells for collecting spats

Plate 2b. Newly constructed oyster farm with rens for spat collection

Plate 3a. Farm with fully grown oyster strings.

Plate 3b. Harvesting of fully grown oysters.

Table 3 Details of experimental farms and sampling

Sl No	Objective	Farm Code	Specification of site	Sampling period / duration	Details of crop / stock
1	Impact due to one year of farming	F1	New farm constructed at a fresh site	Jan 02 to Sep 02 for sediment and benthos, Mar 02 to Sep 02 for hydrography	500 rens placed in Jan 02
2	Impact due to two year of farming at the same site	F2	Same as F-I	Oct 02 to Aug 03 (11 months)	Same rens as in F2
3	Impact due to three years of farming at the same site	F3	Farm of CMFRI where oyster farming is done for the third consecutive year	Jan 02 to Feb 02 (2 months)	500 rens placed by CMFRI staff in April 2001
4	Impact due to four years of farming at the same site	F4	Same farm site as F3	Mar 02 to Aug 02 (6 months)	Fresh rens placed in Mar 02 and harvested in Aug 02.
5	Impact due to five years of farming at the same site	F5	Same farm site as F4	Dec 02 to May 03 (6 months)	Fresh rens placed in Dec 02 and harvested in Jun 03
6	Impact during the crop holiday of three months	CH1	Same as F4 site	Sep 03 to Nov 03 (3 months)	No oyster stock
7	Impact during the crop holiday of six months	CH2	Same as F2 site	Sep 03 to Feb 04 (6 months)	No oyster stock
8	Impact during the crop holiday of nine months	CH3	Same as F5 site	Jun 03 to Feb 04 (9 months)	No oyster stock

3.5 Estimation of farmed oyster biomass

For estimating the oyster biomass, three rens were taken at random from the farm site in each month of sampling. After removing the rens these were washed and brought to the lab. In the laboratory, all the oysters attached on each cultch (3 rens x 5 cultch) were carefully separated. The number of dead and live oysters was noted per cultch. The length (Dorso-ventral measurement, DVM), width (Antereo-posterior measurement, APM), total weight, meat weight and condition index of each of the live oysters were measured. Shell dimensions were measured using a digital vernier calipers (Mikito^{TM}) up to the nearest 0.01 mm and weight to the nearest 0.1 mg using a digital balance. The individual measurements were pooled and from these values average biomass per ren was calculated. Based on this, the average biomass in the farm for each month was estimated. To maintain uniform stocking density throughout the experimental period, three rens from a similar farm constructed near to the experimental farm and having the same age and size group of oysters were replaced after taking the monthly sampling. Care was taken not to remove these rens in the subsequent sampling.

3.6 Impact assessment on hydrographic parameters

3.6.1 Physicochemical parameters

Different physicochemical parameters analysed were temperature, pH and salinity. A representative surface water sample from farm and reference sites was taken in a plastic trough and the measurements were made at the site itself using an appropriate meter.

3.6.1.1 Temperature: Temperature was measured using a hand held mercury bulb thermometer to an accuracy of 0.1^0 C

3.6.1.2 pH: The pH of the water samples was measured with the help of EUTECH water proof pH scan 2 tester

3.6.1.3 Salinity: The salinity of the water sample was measured using ATAGO hand refractometer, which had been calibrated using distilled water.

3.6.2 Column Water Characteristics

Surface water samples beneath 10 cm depth from farm and reference sites were collected in one liter polypropylene carboys during every second week of a month starting from March 2002 to February 2004. Care was exercised to collect a representative water sample from each site during high tide time. The collected samples were immediately transported to the laboratory and kept frozen till the analysis was made.

For dissolved oxygen analysis, water samples from the said sites were collected in glass stopper bottles and were fixed by adding 1 ml each of manganous sulphate and alkaline iodide. They were mixed thoroughly to form precipitation of even distribution. The dissolved oxygen content estimation was carried out in the laboratory as per Winkler method of Strickland and Parsons, (1968).

The different hydrographic parameters estimated from the thawed water samples were (i) Total suspended solids (ii) Chlorophyll and phaeopigments (iii) Nutrient composition (Ammonia, Nitrite, Nitrate and Phosphorous)

3.6.2.1 Total Suspended Solids

An aliquot of 100 ml (or larger) water sample was filtered through a pre dried (at 60^0 C for 24 hours) and pre weighed glass fiber filter grade C paper. The filtration was effected by a vacuum pump. The filter papers were re-dried at 60^0C for 24 hours and reweighed. The total suspended solids was calculated using the formula

$$TSS\ (mg\ L^{-1}) = \frac{(F-T) * 1000}{V}$$

Where F = Final weight of filter paper and residue in milligrams
T = Tare weight of filter paper in milligrams
V = Volume of water filtered in milliliters

3.6.2.2 Chlorophyll and Phaeopigments

A known volume of water sample was filtered through a 47 mm glass fibre grade 'C' filter paper. The pigments were extracted by adding 10 ml of 90% v/v acetone to each filter paper in a flat bottom screw capped glass bottles. The extraction was facilitated by incubating the filter paper bottles under dark conditions

at refrigerated temperature (5-8^{0}C) for overnight. The supernatant after bringing to room temperature was decanted into a cuvette and the extinction was measured at wavelengths of 630, 647, 665, and 750, nm. For phaeopigments content determination extinction was measured before and after acidification with 1 N Hcl at 664 nm. The amount of pigments in the sample was calculated using revised trichromatic equations of Jeffery and Humphrey (1975).

Calculations

$$\text{Chlorophyll a (mg m}^{-3}) = \frac{Ca * VE}{V_F * n}$$

$$\text{Chlorophyll b (mg m}^{-3}) = \frac{Ca * VE}{V_F * n}$$

$$\text{Chlorophyll c (mg m}^{-3}) = \frac{Ca * VE}{V_F * n}$$

$$\text{Phaeopigments (mg m}^{-3}) = \frac{(26.73\,(1.7\,E665b) - E665a)\,VE}{V_F * n}$$

Where: VE = Volume of 90% acetone extract in ml
VF = Water sample filtered in L
n = Light path length in cm
$Ca = 11.85\,E_{664} - 1.54\,E_{647} - 0.08\,E_{630}$
$Cb = 21.03\,E_{647} - 5.43\,E_{664} - 2.66\,E_{630}$
$Cc = 24.52\,E_{630} - 1.67\,E_{664} - 7.6\,E_{647}$
$E_{664} = OD_{664} - OD_{750}$
$E_{647} = OD_{647} - OD_{750}$
$E_{630} = OD_{630} - OD_{750}$
$E_{665b} = OD_{665b} - OD_{750b}$ Before acidification
$E_{665a} = OD_{665a} - OD_{750a}$ After acidification

3.6.2.3 Ammonia

For the determination of ammonia in the water sample, the method involving indophenol blue reaction that of Solarzano (1969) was followed

3.6.2.4 Phosphorous

Phosphorous present in seawater in the form of dissolved orthophosphate was determined quantitatively based on the method given by Murphey and Riley, (1962).

3.6.2.5 Nitrite

The nitrite content present in the seawater sample was determined based on the method of Strickland and Parsons, (1968)

3.6.2.6 Nitrate

The estimation of Nitrate in seawater was based on a method of Morris and Riley (1963) with modifications suggested by Grasshoff (1964) and Wood et al. (1967).

3.7 Impact assessment on the sediment characteristics

3.7.1 Organic carbon content

3.7.1.1 Sample collection and preparation

Replicate sediment samples from the farm and reference sites were collected using a cylindrical PVC corer (80 mm dia x 100 mm high) during every second week of a month starting from January 2002 to February 2004. The core sample was unloaded on to a clean plastic tray without disturbing the sediment column. The sediment column was then divided into two portions of 5 cm each starting from the top sediment surface (labeled as up to 5cm) towards the bottom end (labeled as 5 - 10 cm). The portioned samples were packed separately in heavy duty polythene bags and transported immediately to the laboratory where they were kept frozen in a deep freezer till the analysis was carried out.

Frozen sediment samples were thawed and transferred to a small plastic tray. Then oven dried at 60^0 C for 24 – 48 hours till a constant weight was achieved. The dried sediment sample was then gently racked up and pulverized by breaking clods using a pestle and mortar, sieved through a 0.5 mm mesh sieve and a representative sample was packed in to a self sealing plastic sachet. Such sachets were stored in a dessicator having silica gel as dehydrant.

3.7.1.2 Organic carbon analysis (El Wakeel and Riley, 1957)

0.5 – 2 g of sieved soil was taken in 500 ml conical flask. 10 ml of 1 N potassium dichromate and 20 ml of concentrated sulphuric acid were then added. Shaken well for a minute or two and allowed to stand as it is for about 30 minutes. 200 ml of distilled water, 10 ml of phosphoric acid and 1 ml of diphenylamine indicator solutions were added one after the other and shaken well. The resulting

deep violet colored solution was then titrated against N/2 ferrous ammonium sulphate solution till the color changed to blue and finally to green. In the similar manner a blank determination was made without the soil sample. The percentage of carbon present in soil was calculated using the following formula.

$$\% \text{ of carbon in soil} = \frac{(X - Y) \times N \times 0.003^* \times 100}{W}$$

Where,

X = ml of ferrous ammonium sulphate consumed for blank sample
Y = ml of ferrous ammonium sulpate consumed for sediment sample
N = normality of ferrous ammonium sulphate
W = Weight of soil taken

*1 ml of 1 N potassium dichromate is equivalent to 0.003 g carbon

3.7.2 Particle size

3.7.2.1 Sample collection

Replicate sediment samples from each site were collected as described in 3.7.1.1. Instead of freezing the samples, they were air dried under shade. Then pulverized the sediment gently by breaking clods using a pestle and mortar and packed in self sealing heavy duty polythene bags for later analysis.

3.7.2.2 Mechanical analysis (International pipette method)

The procedure of determining the proportion of mineral particles in to different classes is called particle size analysis or mechanical analysis of the soil. The particle size was analysed based on the method of Krumbein and Petti John, (1938) with some modifications. The method consisted of two distinct steps.

A) **Dispersion:** the cementing substances such as organic matter, colloidal clay and oxides of Fe, Al were removed in this step.
B) **Fractionation**: the sediment samples were fractionated in to different classes based the particle size and its rate of fall through a fluid as expressed by Stokes law.

$$V = 2gr^2 (dp-dw)/9n$$

Where, V = velocity of fall of particles, r = radius of particles, dp = density of particles, dw = density of medium, n = coefficient of viscosity of liquid and g = acceleration due to gravity

A) Dispersion

The procedure consisted of the following steps

1) Accurately weighed a 250 ml beaker
2) Approximately 25 g of air dried soil sample was added in to the beaker
3) About 100 ml of 20 vol. hydrogen peroxide solution was added, stirred well and left to stand as it is for overnight
4) The beaker was placed over a hot plate at 60^0C to destroy the remaining organics. Any liquid frothing up was washed down with distilled water and the whole contents of the beaker were reduced to barest minimum volume
5) After removing from hotplate about 150 ml of distilled water was added by washing down the sides of the beaker, stirred well and allowed to stand overnight.
6) Carefully decanted off as much of the clear liquid as possible without disturbing the solid matter using a pipette.
7) Any remaining liquid was boiled down on a hot plate and then placed the beaker in a drying oven (90 ± 5^0 C) for overnight
8) The beaker was taken out of the drying oven, cooled to room temperature and reweighed. By subtracting the initial weight of the beaker, the weight of the mineral soil free of organic matter was found out.

B) Fractionation

The weight of the peroxidised soil sample in the beaker was recorded. Then moistened with little water and then about 150 ml of distilled water and 10 ml of 5% Sodium hexametaphosphate solution was added. The resulting suspension was stirred well for about 15 minutes to disperse all the aggregates present in soil sample.

1) Separation and Determination of Coarse and Fine Sand Fractions

The soil suspension was poured over a 63µm sieve, retaining the liquid and fine particles beneath the sieve in a tray. Any fine particles present in the beaker and on the sieve were completely transferred through with a jet of distilled water. The fine

suspension from the sieve base was transferred into a 500 ml stopper cylinder. The sand retained on the sieve was washed into a pre weighed evaporating dish and evaporated to dryness in an oven at 95 ± 5^0 C for overnight. Then the dish was cooled and reweighed. The sand thus obtained was quantitatively transferred and sieved through a sieve set of 1mm; 0.5mm + base using a sieve shaker. The fraction of sand retained on each sieve was weighed separately and expressed on percentage dry weight basis. The fraction retained in the sieve base gave fine sand proportion and whereas the sand portion retained on 0.5 mm sieve corresponded to coarse sand fraction.

2) Separation and Determination of Silt + Clay

The soil suspension collected in 500 ml measuring cylinder was filled up to the mark with distilled water, shaken well and placed it in a deep sink filled with water to maintain temperature as near constant as possible. The stem of a 25 ml pipette was marked exactly at 9 cm from its tip. The suspension was again stirred for about half a minute so as to ensure that the soil was evenly distributed throughout the cylinder. The temperature of the suspension and the corresponding time of settling were noted from Table 3. About 20 seconds before the settling time, the pipette was slowly lowered to 10 cm depth and the sample was taken at the exact time that was noted from the table of sedimentation time at different temperature in International system (Table 3). The pipette contents were completely transferred to a weighed crucible and rinsed with distilled water. The crucible was then placed in an oven, evaporated to dryness, cooled and reweighed. From the weight difference the quantity of silt + clay present in 25 ml suspension was calculated and expressed on percentage dry weight basis.

3) Separation and Determination of Clay

The whole suspension was shaken again and kept undisturbed. According to the temperature and time chart 25 ml suspension was drawn in a similar manner as described earlier in to a pre weighed crucible. The crucible was dried at 95 ± 5^0 C in an oven until a constant weight was achieved. The result was expressed on percentage dry weight basis.

4) Separation and Determination of Silt

% silt fraction = (% silt + clay) - % clay

Table 4 Separation of clay and clay + silt at different temperature – time

Temperature	Clay Decantation		Silt Decantation	
(°C)	Hours	Minutes	Minutes	Seconds
11	10	10	6	10
12	9	50	6	0
13	9	35	5	50
14	9	20	5	40
15	9	5	5	30
16	8	50	5	20
17	8	35	5	10
18	8	25	5	0
19	8	10	5	10
20	8	0	4	48
21	7	50	4	40
22	7	40	4	30
23	7	25	4	30
24	7	15	4	20
25	7	5	4	15
26	6	55	4	10
30	6	20	3	50
31	6	15	3	45
33	5	55	3	35

3.8 Impact Assessment on the Benthic Macrofauna

For assessing the impact of oyster culture on benthic macrofauna, replicate sediment samples from farm and reference site were taken using a PVC cylinder (150mm height x 150mm diameter) as suggested by Nugues et al., (1996) during every second week of a month starting from January 2002 to February 2004. Samples were sieved in situ over a 0.5 mm mesh sieve, fixed in 4% buffered formalin and stained with Rose Bengal vital stain. In the laboratory the fauna were sorted to phylum level and preserved in 4% buffered formalin for further identification. The fauna were identified to the lowest possible taxonomic level and classified using standard nomenclature of Fauvel, (1953); Day, (1961) and Gosner, (1971); Sathyamurthi, (1952). The number of each individual species that occurred in a sample and the number of individuals of particular species present in the sample

were noted. The data of replicates was averaged for the purpose of statistical analysis.

3.9. Statistical analyses

Changes in hydrographic parameters and sediment characteristics were analysed using nested model of analysis of variance; where in the variations between the farm and reference sites were nested within the years' effect. This was done to give due weightage to the year effects which had been sequential in nature. Tukey post hoc test was used to reveal the significant differences between the groups. The analysis was accomplished using the GLM procedure of SAS statistical package, Version 9.2. Univariate community measures (number of species, number of individuals) were calculated using the PRIMER statistical software package developed by the Plymouth Marine Laboratory (Clarke & Warwick, 1994). Two measures of species diversity were also calculated: Simpson's reciprocal, D, was chosen as a Type II index which is more sensitive to changes in more abundant species and the exponential of the Shannon – Weiner function (exp H') was used as Type I index, most sensitive to changes in rare species (Peet, 1974). Differences between the values of these statistics were also tested using nested ANOVA of SAS statistical package, Version 9.2.

Comparisons of individuals or gross community parameters such as species richness or diversity may fail to appreciate directional changes in relative species abundance. However these changes may be detectable using multivariate discrimination techniques such as those described in Clarke & Warwick, (1994). The similarity matrix was constructed using the Bray – Curtis similarity index after 4^{th} root transformation of data. The macrobenthic community structure among the sampling sites and between the farming and crop holiday periods was tested using analysis of similarity (ANOSIM). The interpretation of ANOSIM result is based upon the calculation of global R statistic value. R can never technically lie outside the range -1 to 1. R = 1 only if all replicates within sites are more similar to each other than any replicates from different sites. R is approximately zero if the null hypothesis is true, so that similarities between and within sites will be the same on average. The relative contributions of each species to the average similarities of these groupings were calculated using SIMPER analyses.

4.0 RESULTS

4.1 Oyster biomass

The average oyster biomass (meat weight alone) in F1 increased from 27 kg in March to 228 Kg in September and the corresponding total shell-on weight in the farm was 188.4 kg and 1431 Kg respectively (Fig. 2a). The average number of oysters per shell (cultch) was 12 and the estimated number of oyster in the farm was 30,000. In F2 the total biomass ranged between 228.9kg in October 2002 to 458.1 kg in July 2003. The total shell-on weight increased steadily from 1809.6 kg in October 2002 to 3750 kg in Aug 2003 (Fig. 2b). In F3 the biomass ranged between 261.3 kg and 287.7 kg with a shell-on weight of 2555.4 kg and 2697.6 kg respectively (Fig. 3a). In F4 the oyster biomass varied widely, ranging between a low of 345 Kg in Mar 2002 to 488 Kg in Jul 2002. The shell-on weight increased from 2763 kg in Mar 2002 to 3756 kg in Jun 2002. However it decreased in the following two months. In F5 the oyster biomass increased steadily from 85.5 kg in Dec 02 to 267 kg in May 2003 with a corresponding shell-on weight of 258 kg and 1884 kg respectively.

The length of the oysters in F1 farm ranged between 35.3mm and 62.31 mm, width between 25.24 and 50.59mm and depth 13.21 and 25.28mm respectively. In the F2 farm the average length, width and the depth were 75.33 ± 2.32mm, 52.21 ± 5.26mm and 35.22 ± 4.56mm respectively. In F3 and F4, oysters were harvestable size with an average length of 78.63 ± 6.3mm and 82.2 ± 4.8mm, an average width of 52.11 ± 2.33 mm and 56.42 ± 5.32mm respectively. In F5, the length of the oysters increased from 29.22 mm in Dec 2002 to 71.18mm in May 2003. A corresponding increase in width from 19.22 mm to 53.76mm and depth from 10.1 mm to 35 .87 mm of these oysters was observed during the farming period.

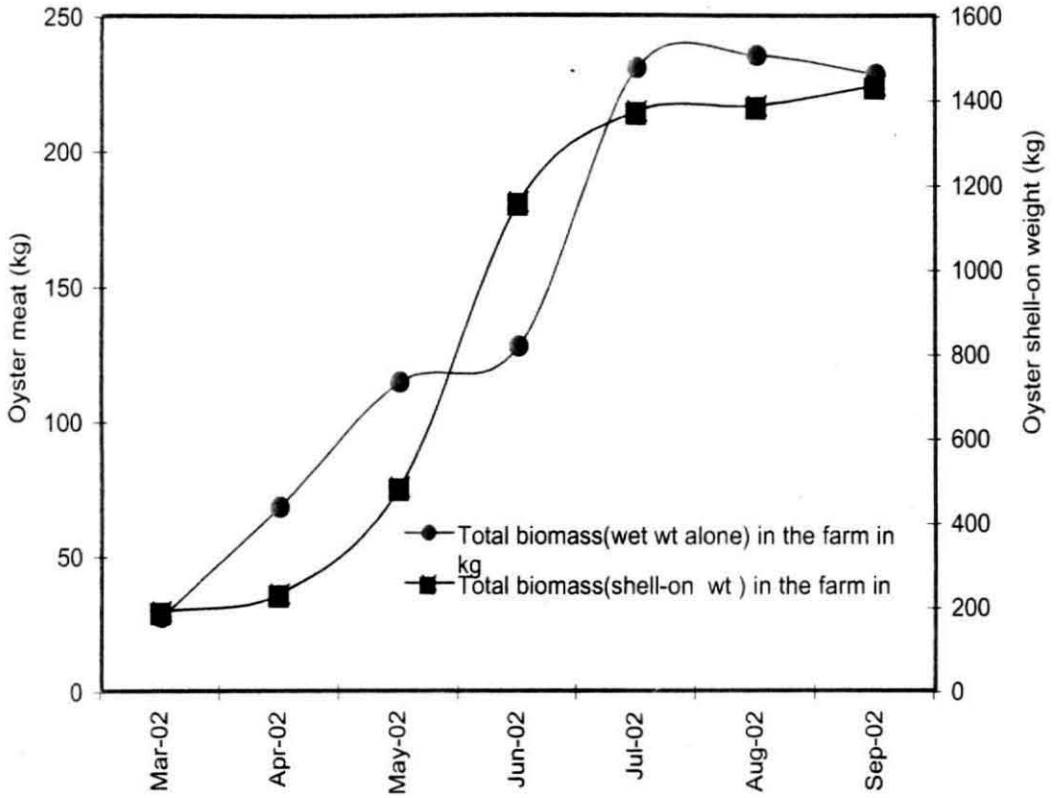

Fig 2a. Monthly variation in oyster biomass in Farm I

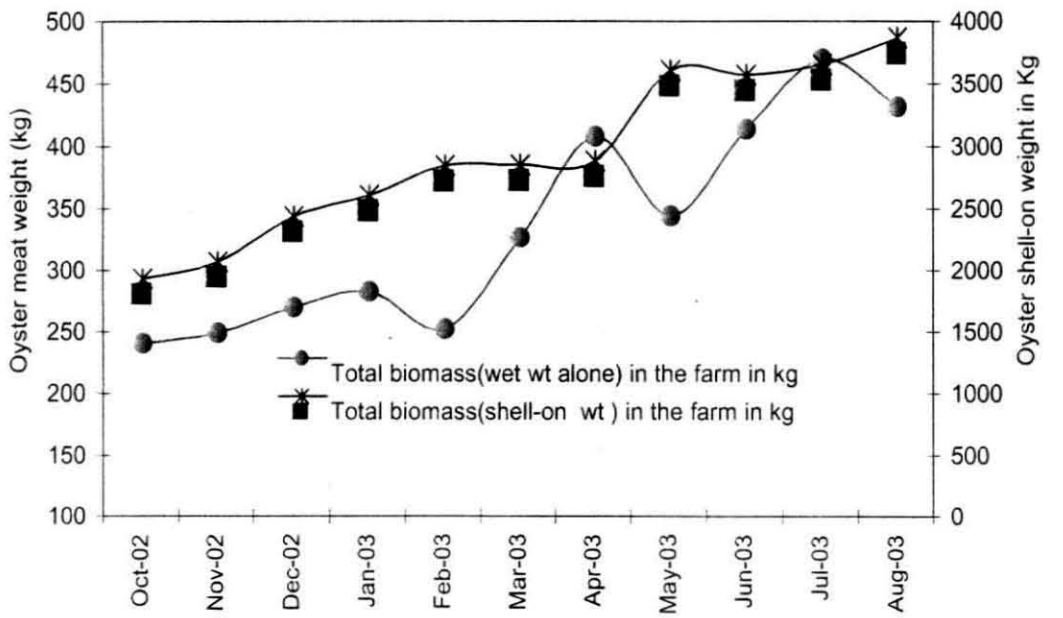

Fig 2b. Monthly variation in oyster biomass in Farm II

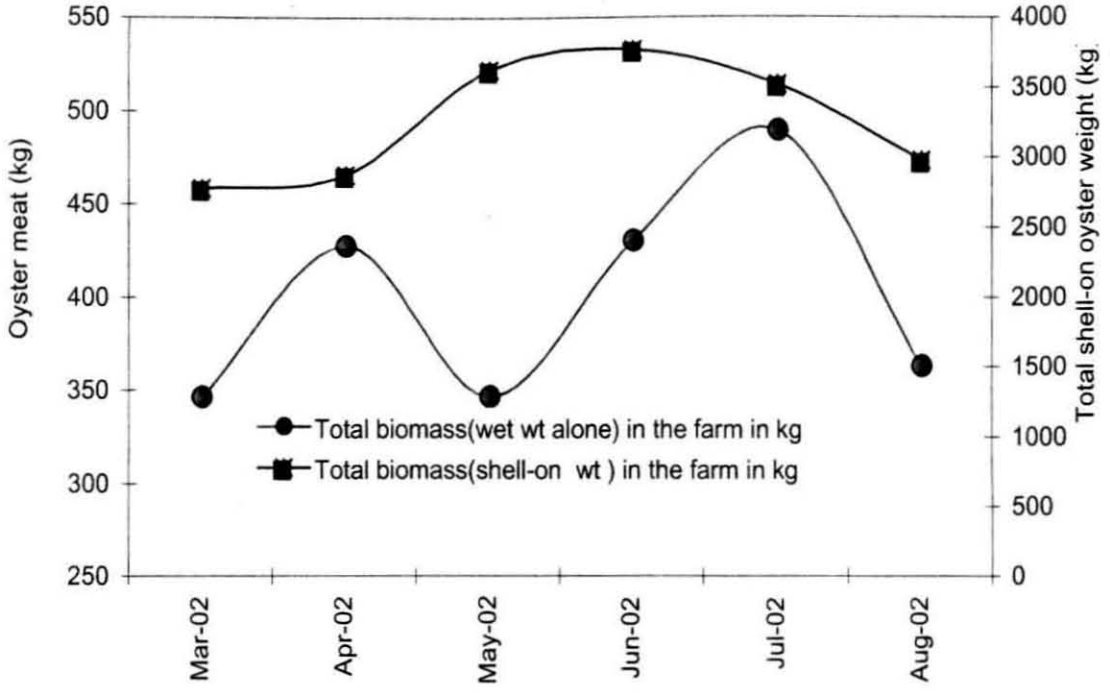

Fig 3a. Monthly variation in oyster biomass in Farm III

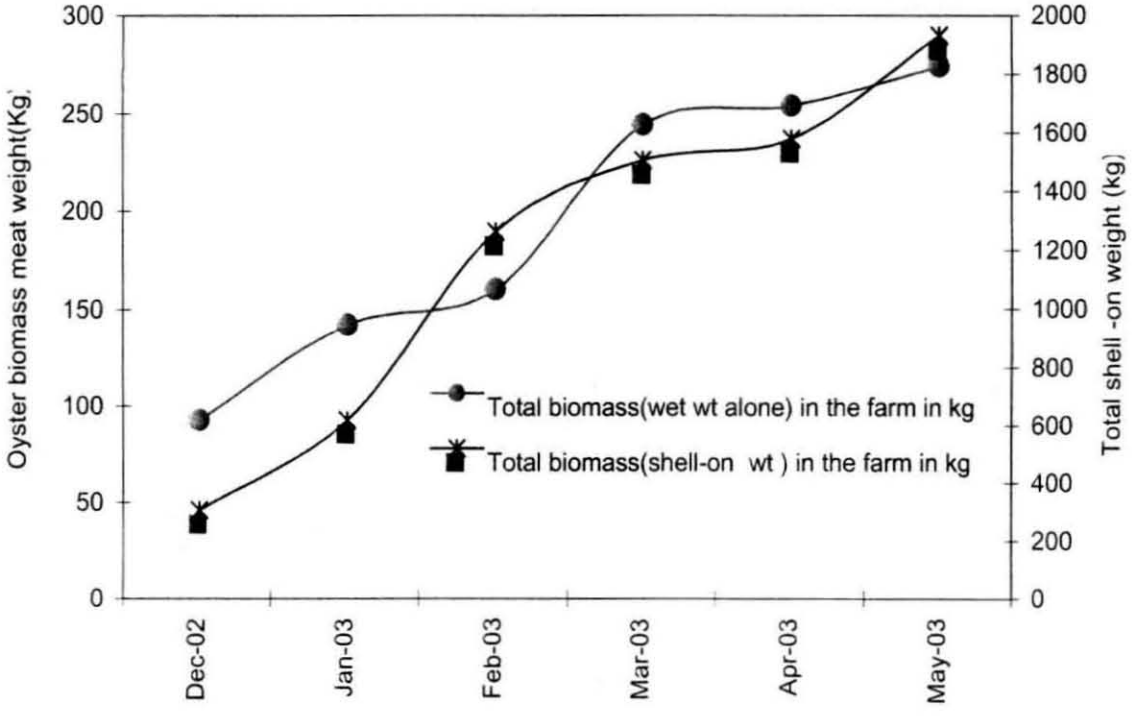

Fig 3b. Monthly variation in oyster biomass in Farm IV

4.2 Impact assessment on hydrographic parameters

The impact of oyster culture on selected hydrographic parameters such as temperature, salinity, pH, dissolved oxygen; total suspended solids, ammonia, phosphate, nitrite, nitrate, and chlorophyll and phaeopigment estimated for the sites of different farming duration (F1, F2, F3, F4 & F5) and corresponding reference sites are presented in Table 5 to 9. The hydrographic values for the sites of different crop holiday period (CH1, CH2, & CH3) with the corresponding reference site values are given in tables 10 to 12.

4.2.1 Temperature

The temperature measured at different sites did not vary much. The maximum values were recorded during May months; and the minimum values during the months of July and December. The mean annual values of temperature measured at farm sites F1, F2, F3, F4, & F5 were 29.4 ± 0.8^{0}C, 30.5 ± 0.7^{0}C, 28.0 ± 0.5^{0}C, 29.6 ± 0.9^{0}C, & 30.2 ± 1.38^{0}C; with a corresponding reference site values of 29.3 ± 0.8^{0}C, 30.4 ± 0.8^{0}C, 28.5 ± 0.5^{0}C, 29.3 ± 0.9^{0}C, & 30.7 ± 1.15^{0}C respectively. The mean temperature values measured at crop holiday and the corresponding reference sites were 30.1 ± 2.2^{0}C and 31.3 ± 1.3^{0}C for CH1; 29.9 ± 0.8^{0}C and 29.6 ± 0.7^{0}C for CH2; 29.9 ± 0.6^{0}C and 29.3 ± 0.6^{0}C for CH3 respectively (Fig. 4). The statistical analysis did not reveal any significant ($p > 0.05$) differences of temperature between the farm and reference sites, and between different years of farming and crop holiday periods.

4.2.2 Salinity

Wide seasonal variations in salinity were observed for all the sites and years of farming and crop holiday periods. The salinity was generally lowest during the southwest monsoon months at F1, F4, sites and during post monsoon sites at F2, F5, CH1, CH2, and CH3. Highest salinity values were generally observed during pre-monsoon months for the farm and reference sites of almost all the farming and crop holiday periods. Mean salinity values recorded at farm with corresponding reference site were 30.0 ± 1.0 ‰ and 29.6 ± 2.0 ‰ for F1; 26.5 ± 1.8 ‰ and 25.5 ± 1.0 ‰ for F2; 29.0 ± 0.5 ‰ and 29.3 ± 0.3 ‰ for F3; 30.2 ± 2.2 ‰ and 30.3 ± 2.1 ‰ for F4; 27.8 ± 1.18 ‰ and 28.0 ± 1.13 ‰ for F5 respectively. The annual mean values

recorded for CH1, CH2, and CH3 with corresponding reference site values were 26.7 ± 5.4 ‰ and 22.0 ± 7.0 ‰; 21.8 ± 4.4 ‰ and 20.3 ± 4.4 ‰; and 24.2 ± 3.0 ‰ and 21.6 ± 3.1 ‰ respectively (Fig. 5). Significant ($p > 0.05$) differences in mean salinity values of farm and reference sites were neither found within the farming or crop holiday period nor between the different farming and crop holiday periods.

4.2.3 pH

The surface water pH remained more or less constant through out the study period at all the sites. The recorded values were around 8.0 ± 0.2 for almost all the months except during the months of February 2002, August 2002 and February 2004. Highest pH values of > 9 were recorded during November 2002 at CH1 and F2 and also at the corresponding reference site. The mean pH recorded at sites of different farming and crop holiday periods with the corresponding reference site values were 8.0 ± 0.1 and 8.0 ± 0.1 for F1, 8.2 ± 0.1 and 8.2 ± 0.1 for F2, 7.9 ± 0.1 and 8.0 ± 0.2 for F3, 8.0 ± 0.1 and 8.0 ± 0.2 for F4, & 8.0 ± 0.06 and 8.0 ± 0.06 for F5; 8.3 ± 0.6 and 8.4 ± 0.6 for CH1, 8.0 ± 0.1 and 8.1 ± 0.1 for CH2, & 8.1 ± 0.1 and 8.1 ± 0.1 for CH3 respectively (Fig. 6). The mean pH values of the sites of different farming and crop holiday periods were not statistically significant ($p > 0.05$).

4.2.4 Dissolved Oxygen

Monthly variations in dissolved oxygen values were quite noticeable in crop holiday sites. The values ranged from 2.8 - 11.3 mg L^{-1} at reference site and 4.0 - 10.9 mg L^{-1} at farm site of CH 3. But on the contrary the dissolved oxygen value of F1, F2, F3, F4 & F5 farm and reference sites did not vary much; the values being in the range of 5 – 8.5 mg L^{-1}. The mean dissolved oxygen content (mg $L^{-}1$) estimated for the sites of different farming and crop holiday periods were 6.5 ± 0.3 for F1, 7.3 ± 0.2 for F2, 7.4 for F3, 6.5 ± 0.5 for F4 and 7.2 ± 0.5 for F5; 7.2 ± 0.6 for CH1, 7.2 ± 0.9 for CH2, and 7.7 ± 0.6 for CH3 with corresponding reference site values of 6.4 ± 0.5, 7.3 ± 0.2, 7.3 ± 0.5, 6.0 ± 0.3, 6.9 ± 0.2; 8.1 ± 0.4, 7.7 ± 1.2, and 7.7 ± 0.8 respectively (Fig. 7). The mean dissolved oxygen content of farm and reference sites within the year of farming and crop holiday periods and between the crop holiday periods was not significantly ($p > 0.05$) different, but between the years of farming significant ($F = 3.23$; $p = 0.0190$) differences were found. The mean dissolved oxygen

of second and fourth year of faming were significantly different (F= 4.21, p = 0.0475 for second year; F= 5.69, p = 0.0206 for fourth year) from the other farming periods.

4.2.5 Total Suspended Solids

High total suspended solids were noticeable during monsoon months at all the farm and reference sites of F1, F2, and F4 and during April, May 2003 for F5; and the low values during pre monsoon months in the farm and reference sites of F1, F3, F4, and F5 and during November 2002 for F2. Generally high as well as low TSS values were observed during post monsoon months at all crop holiday and corresponding reference sites. The mean TSS values (mg L^{-1}) recorded at farm and reference sites of F1, F2, F3, F4, & F5 were 21.9 ± 3.1 and 19.8 ± 1.7, 39.7 ± 11.2 and 29.5 ± 5.6, 17.0 ± 5.0 and 21.5 ± 3.5, 22.4 ± 2.1 and 20.6 ± 1.8, & 42.9 ± 13.8 and 32.6 ± 7.5; and at the crop holiday and corresponding reference sites of CH1, CH2, & CH3 were 19.5 ± 1.8 and 16.1 ± 4.2, 27.4 ± 5.5 and 26.8 ± 5.9, & 44.7 ± 7.5 and 28.5 ± 5.7 respectively (Fig. 8). Even though higher TSS values were recorded at all sites of farming as well as crop holiday periods, they were not significantly ($p > 0.05$) different from the corresponding reference site values. TSS values across the farming and crop holiday periods were also not statistically significant ($p > 0.05$).

4.2.6 Ammonia

Generally high ammonia values were recorded from farm and reference sites of F1, F2, F3, F4 & F5 during April and May months; and low values during February and March months. Very high ammonia values were recorded at all the crop holiday and reference sites during September and February months irrespective of the year. Low values of ammonia were generally recorded during post monsoon months at all the crop holiday sites. The ammonia values of crop holiday sites were generally higher than the farming sties. Mean ammonia values were always higher at the reference sites compared to the farm and crop holiday sites. The ammonia values (µg at NH_3 L^{-1}) estimated for different sites were found to be in the range of 0.1 – 3.0 with a mean of 0.9 ± 0.4 for farm site and 0.1 – 5.7 with a mean of 1.2 ± 0.8 for reference site of F1; 0.1 – 8.1 with a mean of 1.9 ± 0.7 for farm site and 0.0 – 11.0 with a mean of 2.4 ± 1.0 for reference site of F2; 0.2 – 0.6 with a mean of 0.4 ± 0.2 for farm site and 0.2 – 1.9 with a mean of 1.1 ± 0.9 for reference site of F3; 0.0 – 2.1

with a mean of 0.9 ± 0.4 for farm site and 0.1 – 5.7 with a mean of 1.3 ± 0.9 for reference site of F4; 0.1 – 2.1 with a mean of 0.9 ± 0.2 for farm site and 0.1 – 11.0 with a mean of 3.2 ± 1.7 for reference site of F5 respectively. The range and mean ammonia values estimated for crop holiday and corresponding reference sites were found to be 0.2 – 1.5, 0.9 ± 0.5 and 0.9 – 2.6, 1.5 ± 0.7 for CH1; 0.0 – 18.1, 4.7 ± 3.0 and 0.1 – 28.5, 10.5 ± 5.1 for CH2; 1.0 – 7.3, 2.8 ± 0.7 and 0.0 – 28.5, 7.4 ± 3.6 for CH3 respectively (Fig. 9). Even though higher ammonia values were estimated for reference sites, they were not significantly ($p > 0.05$) different from the sites of different farming and crop holiday periods. Ammonia values across the farming and crop holiday periods were also not statistically significant ($p > 0.05$).

4.2.7 Phosphate

Generally high phosphate values were recorded from farm and reference sites of F1, F2 & F4 during July and August months and during March 2003 for F5 sites; and low values were observed during January months at F2, F3 & F5 farming and reference sites. Very high phosphate values were recorded at the crop holiday and corresponding reference sites of CH2 and CH3 during December 2003 and during October 2002 for CH1. Low values of phosphate were generally recorded during January 2004 at CH2 & CH3 sites. The phosphate values of crop holiday sites except CH1 were generally higher than the farming sties. The phosphate values (µg at PO_4 L^{-1}) estimated for different sites were found to be in the range of 0.7 – 4.5 with a mean of 2.1 ± 0.4 for farm site and 0.7 – 9.7 with a mean of 3.0 ± 1.2 for reference site of F1; 0.7 – 4.0 with a mean of 2.1 ± 0.3 for farm site and 0.2 – 3.1 with a mean of 1.6 ± 0.3 for reference site of F2; 0.3 – 2.3 with a mean of 1.3 ± 1.0 for farm site and 0.2 – 2.1 with a mean of 1.2 ± 1.0 for reference site of F3; 0.5 – 2.8 with a mean of 1.6 ± 0.3 for farm site and 1.7 – 9.7 with a mean of 3.4 ± 1.3 for reference site of F4; 0.3 – 2.9 with a mean of 1.7 ± 0.4 for farm site and 0.2 – 3.1 with a mean of 1.6 ± 0.4 for reference site of F5 respectively. The range and mean phosphate values estimated for crop holiday and corresponding reference sites were found to be 1.3 – 2.5, 1.6 ± 0.6 and 0.5 – 2.5, 1.1 ± 0.5 for CH1; 0.2 – 5.2, 2.7 ± 1.0 and 0.5 – 11.2, 4.6 ± 1.9 for CH2; 1.4 – 52.6, 9.1 ± 5.5 and 0.5 – 11.2, 3.7 ± 1.3 for CH3 respectively (Fig. 10). Phosphate values of farm sites of different farming and crop holiday periods were not significantly ($p > 0.05$) different from the corresponding reference site

values. Phosphate values across the farming and crop holiday periods were also not statistically significant ($p>0.05$).

4.2.8 Nitrite

Nitrite values estimated for sites of varying farming periods never exceeded 0.3 µg at NO_2 N L^{-1} and the value was zero for majority of the months of sampling. Generally high nitrite values were recorded from farm and reference sites of F1, F2, & F4 during July months and during May 2003 for F5 sites. Compared to farming sites very high nitrite values were recorded at the crop holiday and corresponding reference sites of CH2 and CH3 during December 2003 and where as nil values were recorded at CH1 sites for all the months of sampling. The nitrite values of crop holiday sites except CH1 were generally higher than the farming sties. The nitrite values (NO_2 -N L^{-1}) estimated for different sites were found to be same with a range of 0.0 – 0.2 and a mean of 0.1 ± 0.0 for farm as well as reference sites of F1, F2, F3, F4 and F5. The range and mean nitrite values estimated for crop holiday and corresponding reference sites were found to be 0.2 – 1.1, 0.4 ± 0.1 and 0.1 – 1.7, 0.4 ± 0.2 for CH2; 0.1 – 1.1, 0.3 ± 0.1 and 0.1 – 1.7, 0.3 ± 0.2 for CH3 respectively (Fig. 11). The values were almost nil for crop holiday as well as reference sites of CH1. Nitrite values of farm as well as crop holiday sites of all the periods were not significantly ($p >0.05$) different from the corresponding reference site values. Nitrite values across the farming and crop holiday periods were also not statistically significant ($p>0.05$).

4.2.9 Nitrate

Nitrate values up to 8.6 NO_3-N L^{-1} were recorded from farming sites. Generally high nitrate values were recorded from farm and reference sites of F1, F3 during July 2002 and during October 2002 for F2 sites; and low values during pre monsoon months. Higher nitrate values were recorded at the crop holiday and corresponding reference sites of CH2 and CH3 during December 2003 and February 2004. Low to zero values of nitrate was generally recorded during monsoon months at all the crop holiday and corresponding reference sites. The nitrate values of the farm as well as crop holiday sites were generally higher than the corresponding reference sites. The nitrate values (µg at NO_3 - N L^{-1}) estimated for different sites were found to be in the

range of 0.1 – 8.1 with a mean of 1.3 ± 1.1 for farm site and 0.0 – 6.1 with a mean of 1.0 ± 0.9 for reference site of F1; 0.0 – 7.9 with a mean of 1.9 ± 0.7 for farm site and 0.0 – 7.5 with a mean of 1.0 ± 0.7 for reference site of F2; 0.2 – 0.3 with a mean of 0.3 ± 0.1 for farm site and 0.2 – 0.3 with a mean of 0.3 ± 0.1 for reference site of F3; 0.1 – 8.6 with a mean of 2.6 ± 1.5 for farm site and 0.0 – 6.1 with a mean of 1.2 ± 1.0 for reference site of F4; 0.0 – 1.3 with a mean of 0.5 ± 0.2 for farm site and 0.0 – 1.3 with a mean of 0.4 ± 0.2 for reference site of F5 respectively. The range and mean ammonia values estimated for crop holiday and corresponding reference sites were found to be 0.3 – 4.2, 1.7 ± 1.6 and 0.3 – 7.5, 2.9 ± 2.8 for CH1; 0.0 – 10.0, 3.6 ± 1.8 and 0.0 – 7.9, 2.1 ± 1.3 for CH2; 0.0 – 6.4, 1.8 ± 0.7 and 0.0 – 7.9, 1.4 ± 0.9 for CH3 respectively (Fig. 12). Nitrate values of farm as well as crop holiday sites of all the periods were not significantly ($p > 0.05$) different from their corresponding reference site values. Nitrate values across the farming and crop holiday periods were also not statistically significant ($p > 0.05$).

4.2.10 Chlorophyll a

Wide fluctuations in chlorophyll a content (mg m^{-3}) were observed between farming and crop holiday sites with the values ranging from 0.0 – 26.3 but with no definite seasonal pattern. The chlorophyll a values were generally higher at crop holiday sites compared to the farming sites. For initial farming periods the chlorophyll a values were generally more at reference sites (F1, F2) but in later periods of farming (F3, F4 & F5) more chlorophyll a values were recorded from farming sites. Crop holiday sites had more chlorophyll a content compared to their corresponding reference sites except CH1. The mean chlorophyll a content of surface water sampled from F1, F2, F3, F4 & F5 farming sites was found to be 2.5 ± 1.1, 8.6 ± 1.6, 2.3 ± 0.1, 2.8 ± 1.6 & 5.9 ± 2.1 with corresponding reference site values of 2.7 ± 1.8, 9.3 ± 2.0, 2.2 ± 0.1, 1.0 ± 0.6 & 4.3 ± 1.0 respectively. The mean chlorophyll a content estimated for different crop holiday sites was found to be 14.4 ± 6.1 for CH1, 8.9 ± 3.1 for CH2 & 13.3 ± 2.5 for CH3, with a corresponding reference site values of 15.2 ± 4.5, 7.2 ± 1.2 & 9.6 ± 1.4 respectively (Fig. 13). The chlorophyll a values of farm and crop holiday sites were not significantly different ($p > 0.05$) from the corresponding reference site values within the farming or crop holiday period. The

chlorophyll a values of F2 were significantly different ($p<0.001$) with all the other farming periods (F1, F3, F4 & F5)

4.2.11 Chlorophyll b

Chlorophyll b content (mg m^{-3}) of farming and the corresponding reference sites varied from 0.0 to 3.3 with no distinct seasonal pattern. The chlorophyll b values at crop holiday sites varied from 0.0 to 5.7, generally November and December months recording high values. The mean chlorophyll b content of surface water sampled from F1, F2, F3, F4 & F5 farming sites was found to be 0.2 ± 0.1, 0.7 ± 0.3, 0.2 ± 0.2, 0.9 ± 0.5 & 0.5 ± 0.2 with corresponding reference site values of 0.2 ± 0.1, 0.7 ± 0.1, 0.6 ± 0.1, 0.2 ± 0.1 & 0.5 ± 0.1 respectively. The mean chlorophyll b content estimated for different crop holiday sites was found to be 0.4 ± 0.4 for CH1, 0.8 ± 0.4 for CH2 & 1.6 ± 0.6 for CH3, with a corresponding reference site values of 0.6 ± 0.3, 1.0 ± 0.4 & 1.0 ± 0.3 respectively (Fig. 14). The chlorophyll b values of farm and crop holiday sites were neither significantly different ($p>0.05$) from their corresponding reference site values within the farming and crop holiday period nor between the farming and crop holiday periods.

4.2.12 Chlorophyll c

Chlorophyll c content (mg m^{-3}) of farming and the corresponding reference sites varied from 0.0 to 12.7, but no distinct seasonal pattern was observed. The chlorophyll c values at crop holiday sites varied from 0.1 to 5.8, generally November and December months recording high chlorophyll c values. The mean chlorophyll c content of crop holiday sites was generally higher than the farming sites. The mean chlorophyll c content of surface water sampled from F1, F2, F3, F4 & F5 farming sites was found to be 0.3 ± 0.1, 1.2 ± 0.4, 0.3 ± 0.1, 0.9 ± 0.4 & 2.5 ± 2.0 with corresponding reference site values of 0.4 ± 0.2, 1.3 ± 0.3, 0.7 ± 0.2, 0.3 ± 0.2 & 0.8 ± 0.2 respectively. The mean chlorophyll c content estimated for different crop holiday sites was found to be 1.7 ± 1.3 for CH1, 1.6 ± 0.5 for CH2 & 2.6 ± 0.6 for CH3, with a corresponding reference site values of 1.9 ± 1.1, 1.8 ± 0.6 & 1.8 ± 0.4 respectively (Fig. 15). The chlorophyll c values of farm and crop holiday sites were neither significantly different ($p>0.05$) from their corresponding reference site values

within the farming and crop holiday period nor between the farming and crop holiday periods.

4.2.13 Phaeopigment

Very wide monthly variations (0 – 104 mg m^{-3}) in phaeopigment content were recorded from all the sites. Phaeopigment values (mg m^{-3}) were generally high during monsoonal months at F1, F2, & F5 sites and during February 2002 at F3 and F5 sites. Higher phaeopingment values were recorded from CH1 and CH2 sites during October & November months and during August 2003 for CH3 sites. The phaeopigment values of crop holiday sites were generally higher than the farming sites and the values generally increased when a crop holiday of 3-9 months was given following farming phase. The mean phaeopigment content of surface water sampled from F1, F2, F3, F4 & F5 farming sites was found to be 10.1 ± 4.3, 34.2 ± 6.3, 20.9 ± 5.5, 11.2 ± 6.3 & 23.3 ± 8.2 with corresponding reference site values of 10.6 ± 6.9, 36.6 ± 7.9, 16.8 ± 6.6, 3.9 ± 2.4 & 17 ± 4.2 respectively. The mean phaeopigment content estimated for different crop holiday sites was found to be 56.6 ± 24.0 for CH1, 29.7± 11.4 for CH2 & 52.9 ± 9.9 for CH3, with corresponding reference site values of 60.2 ± 17.7, 27.9 ± 4.6 & 37.5 ± 5.8 respectively (Fig. 16). The phaeopigment values of farm and crop holiday sites were not significantly different ($p>0.05$) from their corresponding reference site values within the farming or crop holiday period. The phaeopigment values of F2 & F4 were significantly different ($p<0.001$ for F2, $p< 0.0308$ for F4) with all the other farming periods (F1, F3 & F5). Similarly the phaeopigment values of CH1 were significantly different ($p< 0.0161$) from CH2 & CH3 values.

Table 5 Hydrographic parameters for the farm and reference site of one year farming duration (F1)

Parameter	Site	Month						
		Mar/02	Apr/02	May/02	Jun/02	Jul/02	Aug/02	Sep/02
Temperature (^{0} C)	Farm	31.5	28.0	28.0	30.0	32.0	29.3	27.0
	Reference	31.0	27.0	28.0	28.5	31.0	29.7	27.0
Salinity (‰)	Farm	29.0	30.0	17.0	30.0	10.0	30.5	31.0
	Reference	29.0	27.0	16.0	27.0	6.0	27.0	28.0
pH	Farm	8.0	8.1	8.2	7.8	8.3	8.2	8.2
	Reference	8.1	8.1	8.3	7.8	8.3	8.3	8.3
Dissolved oxygen (mg L^{-1})	Farm	7.7	7.7	6.9	4.0	10.9	7.3	8.9
	Reference	7.7	7.7	8.1	2.8	11.3	6.5	8.9
Total suspended	Farm	50.4	69.1	62.4	34.4	17.2	51.9	76.0
solids (mg L^{-1})	Reference	26.4	9.8	59.6	34.4	15.6	22.4	52.4
Ammonia (µg NH_3 L^{-1})	Farm	1.0	1.1	1.5	4.3	2.3	1.1	2.1
	Reference	3.2	0.0	0.3	28.5	0.9	0.1	1.7
Phosphate (µg PO_4 L^{-1})	Farm	1.2	3.6	2.1	6.4	52.6	5.0	9.0
	Reference	0.7	3.1	1.4	4.5	0.5	9.3	11.2
Nitrite (µg NO_2 - N L^{-1})	Farm	0.1	0.4	0.1	0.3	0.2	0.5	1.1
	Reference	0.1	0.1	0.1	0.2	0.1	0.3	1.7
Nitrate (µg NO_3 - N L^{-1})	Farm	0.0	3.5	0.3	0.0	0.0	1.0	6.4
	Reference	0.0	0.0	0.0	0.0	0.0	0.7	7.9
Chlorophyll a (mg m^{-3})	Farm	17.0	17.2	26.3	3.8	18.0	15.5	11.2
	Reference	12.9	13.9	16.3	4.8	11.8	7.9	4.0
Chlorophyll b (mg m^{-3})	Farm	1.4	1.5	2.8	0.5	0.0	5.7	2.1
	Reference	0.7	1.0	1.4	0.3	1.3	0.8	3.0
Chlorophyll c (mg m^{-3})	Farm	3.0	4.3	3.3	0.5	2.4	5.8	3.1
	Reference	1.2	2.3	1.8	1.2	1.4	1.4	4.6
Phaeopigment (mg m^{-3})	Farm	67.3	68.0	104.1	15.2	70.9	62.7	44.6
	Reference	51.2	54.8	64.6	18.8	46.4	31.4	17.0

Table 6 Hydrographic parameters for the farm and reference site of two year farming duration (F2)

		Month										
Parameter	Site	Oct/02	Nov/02	Dec/02	Jan/03	Feb/03	Mar/03	Apr/03	May/03	Jun/04	Jul/03	Aug/03
Temperature (^{0} C)	Farm	32.4	31.7	29.0	28.2	27.5	31.5	32.0	35.0	32.0	28.5	28.0
	Reference	32.9	31.7	28.0	28.0	29.0	32.0	32.0	35.0	31.0	27.0	28.0
Salinity (‰)	Farm	32.4	14.0	26.0	28.2	29.0	30.0	32.0	25.0	30.0	28.5	16.0
	Reference	30.0	11.0	25.0	28.0	28.0	30.0	32.0	25.0	29.0	27.0	16.0
pH	Farm	7.8	9.4	8.1	8.0	7.7	8.1	8.0	8.2	8.1	8.1	8.3
	Reference	7.9	9.3	8.1	8.1	7.8	8.0	8.0	8.2	8.1	8.1	8.3
Dissolved oxygen (mg L^{-1})	Farm	7.4	8.1	5.5	7.4	7.4	5.8	8.5	8.4	7.7	7.7	6.9
	Reference	7.3	8.1	7.1	6.8	7.7	6.4	6.1	7.0	7.7	7.7	8.1
Total suspended	Farm	19.6	12.4	18.4	17.0	32.4	17.8	60.0	70.4	18.8	32.8	136.6
solids (mg L^{-1})	Reference	22.6	10.8	20.2	32.6	15.4	22.0	65.2	40.4	26.4	9.8	59.6
Ammonia (µg NH_3 L^{-1})	Farm	0.4	1.6	1.6	0.7	0.1	0.7	4.4	2.1	0.8	8.1	0.5
	Reference	1.0	2.6	1.1	1.9	0.1	0.3	5.1	11.0	3.2	0.0	0.3
Phosphate (µg PO_4 L^{-1})	Farm	2.8	1.7	1.3	0.7	1.3	3.3	3.3	1.2	1.0	4.0	2.1
	Reference	2.2	0.5	1.8	0.2	2.2	3.1	1.4	1.2	0.7	3.1	1.4
Nitrite (µg NO_2 - N L^{-1})	Farm	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.1
	Reference	0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.3	0.1	0.1	0.1
Nitrate (µg NO_3 - N L^{-1})	Farm	7.9	0.7	1.1	0.4	0.2	0.0	3.4	3.8	0.1	3.3	0.3
	Reference	7.5	1.0	1.3	0.3	0.2	0.0	0.0	0.9	0.0	0.0	0.0
Chlorophyll a (mg m^{-3})	Farm	12.6	7.4	2.0	2.0	10.0	2.0	6.2	8.6	14.3	12.3	17.7
	Reference	10.5	22.5	1.2	2.0	6.8	3.0	6.5	6.3	12.9	13.9	16.3
Chlorophyll b (mg m^{-3})	Farm	0.0	1.4	0.2	0.1	0.2	0.2	0.5	0.9	1.1	0.2	3.2
	Reference	0.4	1.0	0.0	0.5	0.6	0.1	1.0	0.8	0.7	1.0	1.4
Chlorophyll c (mg m^{-3})	Farm	0.0	1.3	0.0	0.0	1.0	0.2	1.1	1.2	2.6	2.1	4.0
	Reference	0.7	3.8	0.2	0.6	0.9	0.4	1.8	1.0	1.2	2.3	1.8
Phaeopigment (mg m^{-3})	Farm	48.9	29.5	8.1	8.1	39.4	8.0	24.4	34.1	56.5	48.3	70.6
	Reference	41.8	88.7	4.5	8.1	26.8	11.6	25.9	25.1	51.2	54.8	64.6

Table 7 Hydrographic parameters for the farm and reference site of three year farming duration (F3)

Parameter	Site	Month	
		Jan/02	Feb/02
Temperature (^{0} C)	Farm	28.5	27.5
	Reference	28.0	29.0
Salinity (‰)	Farm	29.5	28.5
	Reference	29.5	29.0
pH	Farm	8.0	7.8
	Reference	8.1	7.8
Dissolved oxygen (mg L^{-1})	Farm	7.4	7.4
	Reference	6.8	7.7
Total suspended	Farm	22.0	12.0
solids (mg L^{-1})	Reference	25.0	18.0
Ammonia (µg at NH_3 L^{-1})	Farm	0.6	0.2
	Reference	1.9	0.2
Phosphate (µg PO_4 L^{-1})	Farm	0.3	2.3
	Reference	0.2	2.1
Nitrite (µg NO_2 - N L^{-1})	Farm	0.1	0.1
	Reference	0.1	0.2
Nitrate (µg NO_3 - N L^{-1})	Farm	0.3	0.2
	Reference	0.3	0.2
Chlorophyll a (mg m^{-3})	Farm	2.4	2.2
	Reference	2.3	2.1
Chlorophyll b (mg m^{-3})	Farm	0.0	0.4
	Reference	0.5	0.6
Chlorophyll c (mg m^{-3})	Farm	0.2	0.3
	Reference	0.5	0.9
Phaeopigment (mg m^{-3})	Farm	15.4	26.3
	Reference	10.2	23.3

Table 8 Hydrographic parameters for the farm and reference site of four year farming duration (F4)

Parameter	Site	Month					
		Mar/02	Apr/02	May/02	Jun/02	Jul/02	Aug/02
Temperature (^{0} C)	Farm	30.8	30.5	32.5	29.0	26.0	29.0
	Reference	30.2	31.0	31.8	29.0	25.5	28.2
Salinity (‰)	Farm	35.0	35.0	26.0	25.0	35.0	25.0
	Reference	34.0	36.0	27.0	25.0	35.0	25.0
pH	Farm	8.1	8.2	8.1	8.1	8.1	7.6
	Reference	8.1	8.3	8.1	8.1	8.1	7.1
Dissolved oxygen (mg L^{-1})	Farm	5.7	8.5	5.3	5.8	6.4	7.4
	Reference	6.9	6.1	6.9	5.4	5.8	5.1
Total suspended	Farm	25.1	17.0	18.0	31.0	20.0	23.2
solids (mg L^{-1})	Reference	12.0	24.4	21.0	22.3	22.9	20.8
Ammonia (µg at NH_3 L^{-1})	Farm	0.0	2.1	1.8	0.3	0.9	0.3
	Reference	0.2	5.7	1.2	0.4	0.2	0.1
Phosphate (µg PO_4 L^{-1})	Farm	2.0	1.8	1.0	1.7	0.5	2.8
	Reference	2.2	1.2	1.7	2.5	9.7	3.0
Nitrite (µg NO_2 - N L^{-1})	Farm	0.2	0.0	0.0	0.2	0.1	0.1
	Reference	0.1	0.2	0.1	0.0	0.2	0.1
Nitrate (µg NO_3 - N L^{-1})	Farm	0.1	0.1	0.3	1.1	8.6	5.4
	Reference	0.1	0.2	0.2	0.3	6.1	0.0
Chlorophyll a (mg m^{-3})	Farm	0.5	2.4	2.4	0.6	10.4	0.4
	Reference	0.2	0.0	0.0	0.0	3.3	2.5
Chlorophyll b (mg m^{-3})	Farm	0.0	0.5	0.5	0.8	3.3	0.5
	Reference	0.3	0.0	0.0	0.0	0.4	0.3
Chlorophyll c (mg m^{-3})	Farm	0.0	0.6	0.6	0.4	2.9	0.6
	Reference	0.3	0.0	0.0	0.0	0.3	1.0
Phaeopigment (mg m^{-3})	Farm	1.9	9.6	9.6	2.7	41.9	1.8
	Reference	0.9	0.0	0.0	0.0	12.9	9.9

Table 9 Hydrographic parameters for the farm and reference site of five year farming duration (F5)

		Month					
Parameter	Site	Dec/02	Jan/02	Feb/02	Mar/02	Apr/02	May/03
Temperature (^{0} C)	Farm	26.0	28.5	27.5	32.0	32.0	35.0
	Reference	28.0	28.0	29.0	32.0	32.0	35.0
Salinity (‰)	Farm	26.0	28.5	25.0	30.0	32.0	25.0
	Reference	25.0	28.0	28.0	30.0	32.0	25.0
pH	Farm	8.1	8.0	7.8	8.1	8.0	8.2
	Reference	8.1	8.1	7.8	8.0	8.0	8.2
Dissolved oxygen (mg L^{-1})	Farm	5.5	7.4	7.4	5.8	8.5	8.4
	Reference	7.1	6.8	7.7	6.4	6.1	7.0
Total suspended solids (mg L^{-1})	Farm	21.4	18.8	12.0	46.2	56.8	102.3
	Reference	20.2	32.6	15.4	22.0	65.2	40.4
Ammonia (µg NH_3 L^{-1})	Farm	1.2	0.6	0.1	0.5	1.1	2.1
	Reference	1.1	1.9	0.1	0.3	5.1	11.0
Phosphate (µg PO_4 L^{-1})	Farm	0.5	0.3	2.7	2.9	2.4	1.4
	Reference	1.8	0.2	2.2	3.1	1.4	1.2
Nitrite (µg NO_2 - N L^{-1})	Farm	0.0	0.0	0.1	0.2	0.1	0.2
	Reference	0.1	0.0	0.0	0.1	0.1	0.3
Nitrate (µg NO_3 - N L^{-1})	Farm	0.1	0.3	0.2	0.0	0.8	1.3
	Reference	1.3	0.3	0.2	0.0	0.0	0.9
Chlorophyll a (mg m^{-3})	Farm	3.0	2.1	5.7	3.4	5.2	15.8
	Reference	1.2	2.0	6.8	3.0	6.5	6.3
Chlorophyll b (mg m^{-3})	Farm	0.1	0.0	0.4	0.9	0.1	1.4
	Reference	0.0	0.5	0.6	0.1	1.0	0.8
Chlorophyll c (mg m^{-3})	Farm	0.4	0.0	0.4	12.7	0.0	1.5
	Reference	0.2	0.6	0.9	0.4	1.8	1.0
Phaeopigment (mg m^{-3})	Farm	11.7	8.1	22.4	14.3	20.5	62.8
	Reference	4.5	8.1	26.8	11.6	25.9	25.1

Table 10 Hydrographic parameters for the crop holiday and reference site of three months crop holiday period (CH1)

Parameter	Site	Month		
		Sept' 02	Oct	Nov'02
Temperature (^{0} C)	Farm	26.6	32.2	31.5
	Reference	29.2	32.9	31.7
Salinity (‰)	Farm	30.0	32.2	18.0
	Reference	25.0	30.0	11.0
pH	Farm	7.8	7.7	9.2
	Reference	8.0	7.9	9.3
Dissolved oxygen (mg L^{-1})	Farm	8.1	0.7	0.4
	Reference	8.8	7.3	8.1
Total suspended solids (mg L^{-1})	Farm	16.6	21.6	20.4
	Reference	14.9	22.6	10.8
Ammonia (µg NH_3 L^{-1})	Farm	0.8	0.2	1.5
	Reference	0.9	1.0	2.6
Phosphate (µg PO_4 L^{-1})	Farm	1.3	2.5	1.0
	Reference	0.7	2.2	0.5
Nitrite (µg NO_2 - N L^{-1})	Farm	0.0	0.0	0.0
	Reference	0.0	0.0	0.1
Nitrate (µg NO_3 - N L^{-1})	Farm	0.3	4.2	0.6
	Reference	0.3	7.5	1.0
Chlorophyll a (mg m^{-3})	Farm	7.9	11.2	24.1
	Reference	12.7	10.5	22.5
Chlorophyll b (mg m^{-3})	Farm	0.0	0.1	1.0
	Reference	0.2	0.4	1.0
Chlorophyll c (mg m^{-3})	Farm	0.9	0.4	3.7
	Reference	1.3	0.7	3.8
Phaeopigment (mg m^{-3})	Farm	30.9	43.9	95.0
	Reference	50.2	41.8	88.7

Table 11 Hydrographic parameters for the crop holiday and reference site of six months crop holiday period (CH2)

Parameter	Site	Month					
		Sep/03	Oct/03	Nov/03	Dec/03	Jan/03	Feb/04
Temperature (^{0} C)	Farm	29.0	32.0	29.0	27.0	32.0	30.5
	Reference	28.5	31.0	29.7	27.0	31.0	30.5
Salinity (‰)	Farm	30.0	8.0	30.0	28.0	8.0	27.0
	Reference	27.0	6.0	27.0	28.0	7.0	27.0
pH	Farm	7.8	8.1	8.2	8.2	8.1	7.5
	Reference	7.8	8.3	8.3	8.3	8.3	7.6
Dissolved oxygen (mg L^{-1})	Farm	4.0	8.9	5.7	8.1	6.9	9.7
	Reference	2.8	11.3	6.5	8.9	7.3	9.3
Total suspended solids (mg L^{-1})	Farm	46.0	17.8	21.6	43.2	17.8	18.0
	Reference	34.4	15.6	22.4	52.4	15.4	20.4
Ammonia (µg NH_3 L^{-1})	Farm	18.1	0.8	1.2	0.0	0.0	8.1
	Reference	28.5	0.9	0.1	1.7	8.5	23.5
Phosphate (µg PO_4 L^{-1})	Farm	5.2	1.2	4.3	4.8	0.2	0.2
	Reference	4.5	0.5	9.3	11.2	0.7	1.4
Nitrite (µg NO_2 - N L^{-1})	Farm	0.3	0.3	0.6	1.1	0.2	0.2
	Reference	0.2	0.1	0.3	1.7	0.2	0.1
Nitrate (µg NO_3 - N L^{-1})	Farm	0.5	0.0	1.1	8.6	1.2	10.0
	Reference	0.0	0.0	0.7	7.9	0.8	3.1
Chlorophyll a (mg m^{-3})	Farm	5.2	21.4	14.7	1.6	2.7	7.7
	Reference	4.8	11.8	7.9	4.0	6.1	8.4
Chlorophyll b (mg m^{-3})	Farm	0.5	0.5	1.5	2.2	0.0	0.1
	Reference	0.3	1.3	0.8	3.0	0.1	0.2
Chlorophyll c (mg m^{-3})	Farm	1.0	2.9	3.0	1.5	0.1	1.3
	Reference	1.2	1.4	1.4	4.6	1.3	1.0
Phaeopigment (mg m^{-3})	Farm	20.6	84.3	23.3	7.1	12.7	30.5
	Reference	18.8	46.4	31.4	17.0	20.6	33.1

Table 12 Hydrographic parameters for the crop holiday and reference site of nine months crop holiday period (CH3)

Parameter	Site	Month								
		Jun/03	Jul/03	Aug/03	Sep/03	Oct/03	Nov/03	Dec/03	Jan/03	Feb/04
Temperature (^{0} C)	Farm	31.5	28.0	28.0	30.0	32.0	29.3	27.0	32.0	31.0
	Reference	31.0	27.0	28.0	28.5	31.0	29.7	27.0	31.0	30.5
Salinity (‰)	Farm	29.0	30.0	17.0	30.0	10.0	30.5	31.0	10.0	30.0
	Reference	29.0	27.0	16.0	27.0	6.0	27.0	28.0	7.0	27.0
pH	Farm	8.0	8.1	8.2	7.8	8.3	8.2	8.2	8.3	7.4
	Reference	8.1	8.1	8.3	7.8	8.3	8.3	8.3	8.3	7.6
Dissolved oxygen (mg L^{-1})	Farm	7.7	7.7	6.9	4.0	10.9	7.3	8.9	6.9	9.3
	Reference	7.7	7.7	8.1	2.8	11.3	6.5	8.9	7.3	9.3
Total suspended	Farm	50.4	69.1	62.4	34.4	17.2	51.9	76.0	22.6	18.2
solids (mg L^{-1})	Reference	26.4	9.8	59.6	34.4	15.6	22.4	52.4	15.4	20.4
Ammonia (µg NH_3 L^{-1})	Farm	1.0	1.1	1.5	4.3	2.3	1.1	2.1	4.2	7.3
	Reference	3.2	0.0	0.3	28.5	0.9	0.1	1.7	8.5	23.5
Phosphate (µg PO_4 L^{-1})	Farm	1.2	3.6	2.1	6.4	52.6	5.0	9.0	1.4	0.7
	Reference	0.7	3.1	1.4	4.5	0.5	9.3	11.2	0.7	1.4
Nitrite (µg NO_2 - N L^{-1})	Farm	0.1	0.4	0.1	0.3	0.2	0.5	1.1	0.2	0.1
	Reference	0.1	0.1	0.1	0.2	0.1	0.3	1.7	0.2	0.1
Nitrate (µg NO_3 - N L^{-1})	Farm	0.0	3.5	0.3	0.0	0.0	1.0	6.4	3.5	1.7
	Reference	0.0	0.0	0.0	0.0	0.0	0.7	7.9	0.8	3.1
Chlorophyll a (mg m^{-3})	Farm	17.0	17.2	26.3	3.8	18.0	15.5	11.2	3.7	7.3
	Reference	12.9	13.9	16.3	4.8	11.8	7.9	4.0	6.1	8.4
Chlorophyll b (mg m^{-3})	Farm	1.4	1.5	2.8	0.5	0.0	5.7	2.1	0.0	0.0
	Reference	0.7	1.0	1.4	0.3	1.3	0.8	3.0	0.1	0.2
Chlorophyll c (mg m^{-3})	Farm	3.0	4.3	3.3	0.5	2.4	5.8	3.1	0.3	0.7
	Reference	1.2	2.3	1.8	1.2	1.4	1.4	4.6	1.3	1.0
Phaeopigment (mg m^{-3})	Farm	67.3	68.0	104.1	15.2	70.9	62.7	44.6	14.4	28.7
	Reference	51.2	54.8	64.6	18.8	46.4	31.4	17.0	20.6	33.1

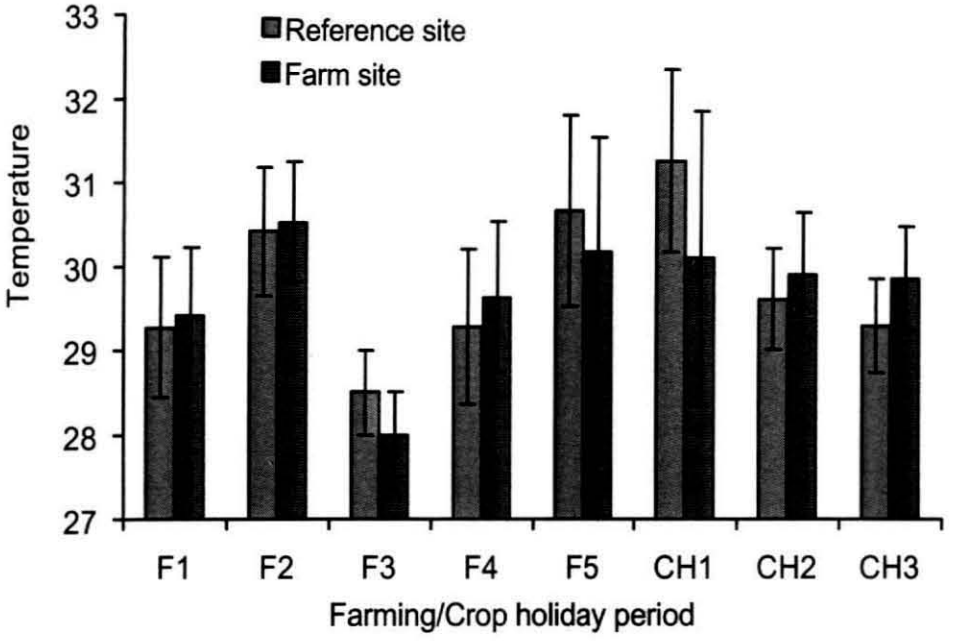

Figure 4. Mean (SE) values of temperature at different farming and crop holiday periods. Vertical bars indicate standard error

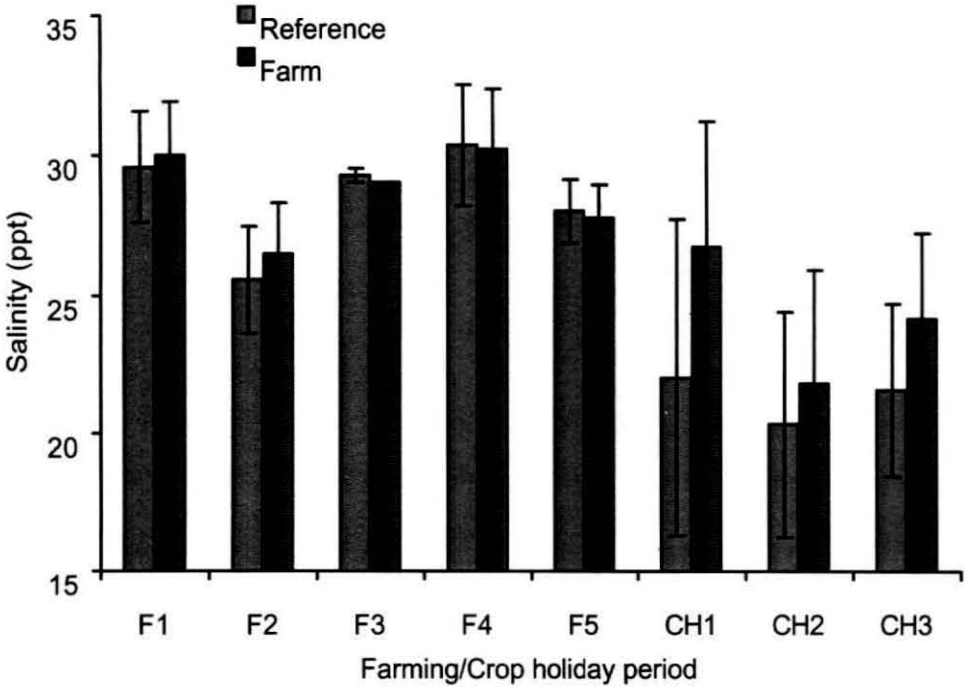

Figure 5. Mean values of Salinity at different farming and crop holiday periods. Vertical bars indicate standard error

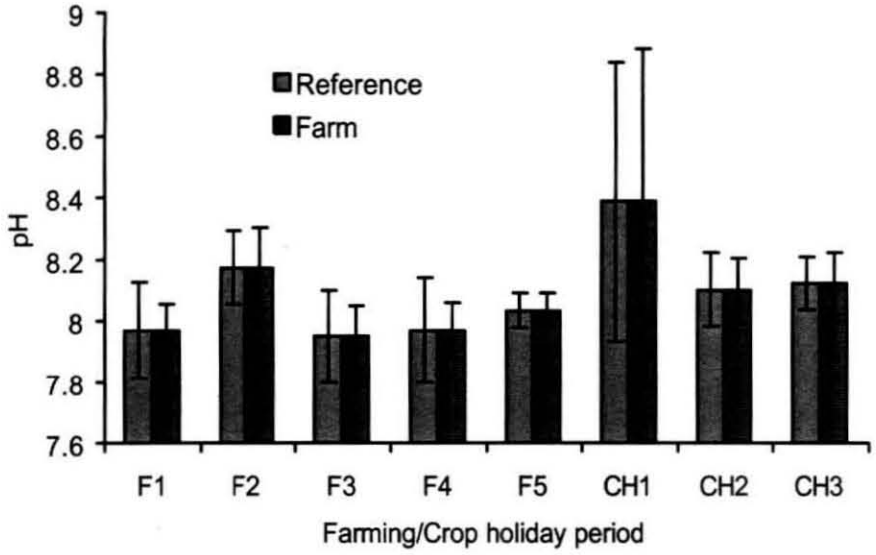

Figure 6. Mean values of pH at different farming and crop holiday periods. Vertical bars indicate standard error

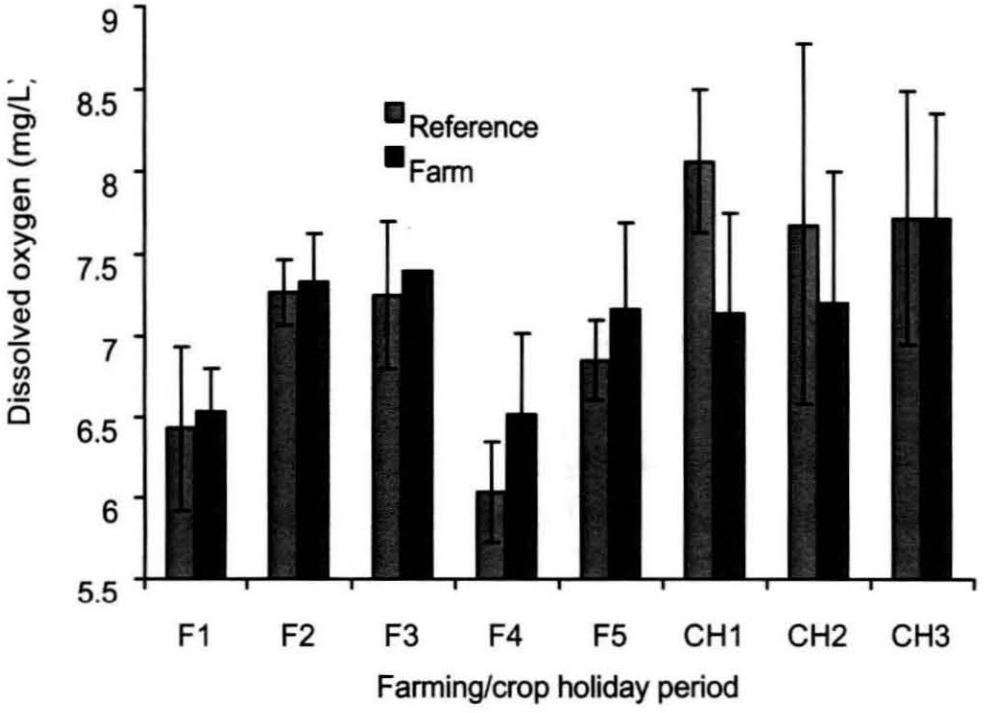

Figure 7. Mean values of dissolved oxygen at different farming and crop holiday sites. Vertical bars indicate standard error

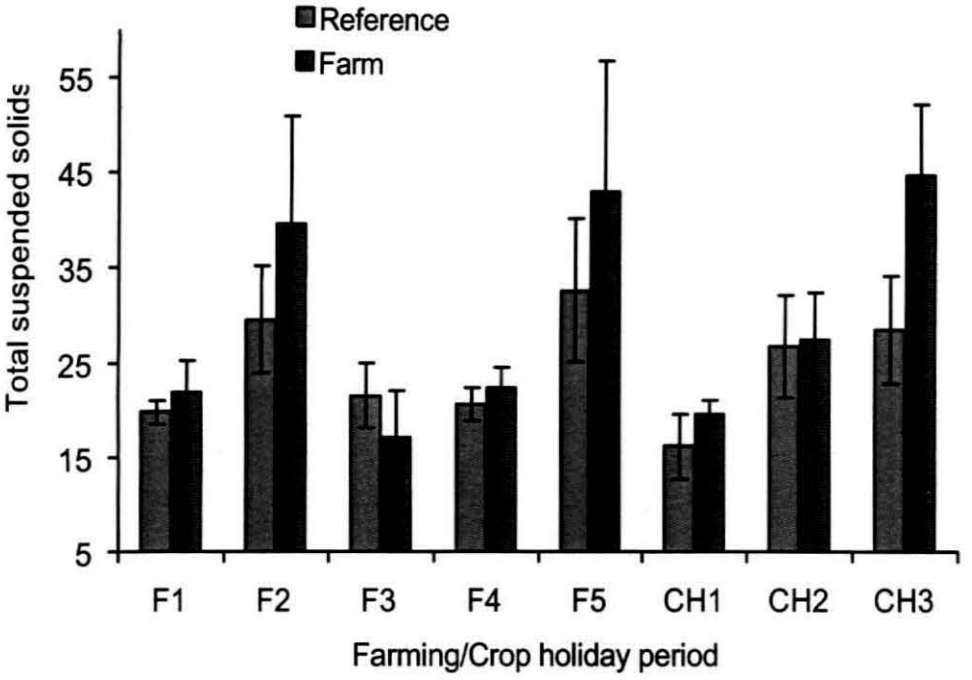

Figure 8. Mean values total suspended solids at different farming and crop holiday periods. Vertical bars indicate standard error

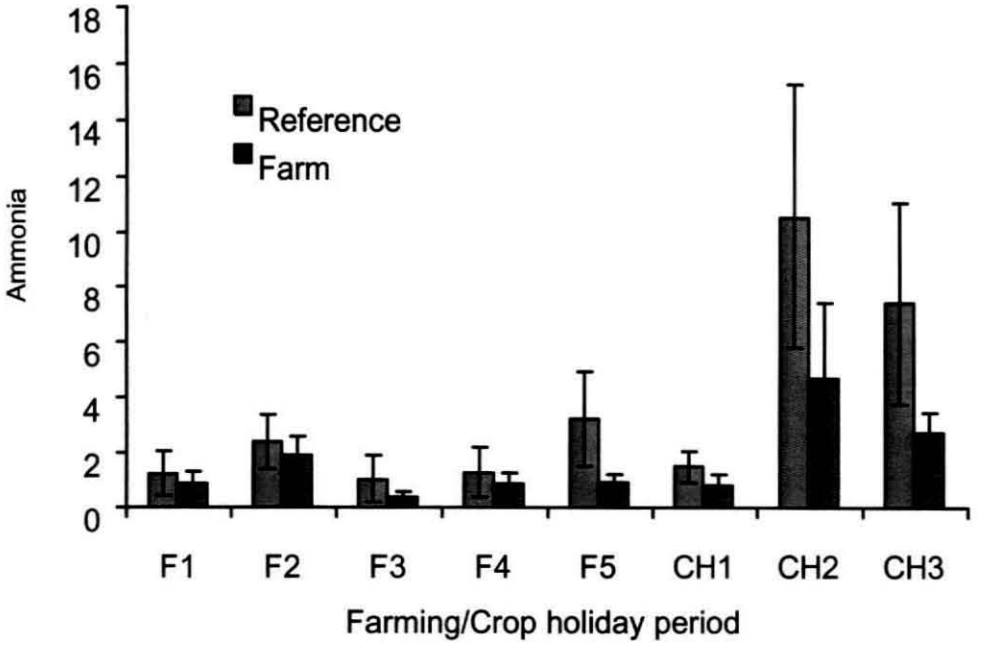

Figure 9. Mean values of ammonia at different farming and crop holiday sites. Vertical bars indicate standard error

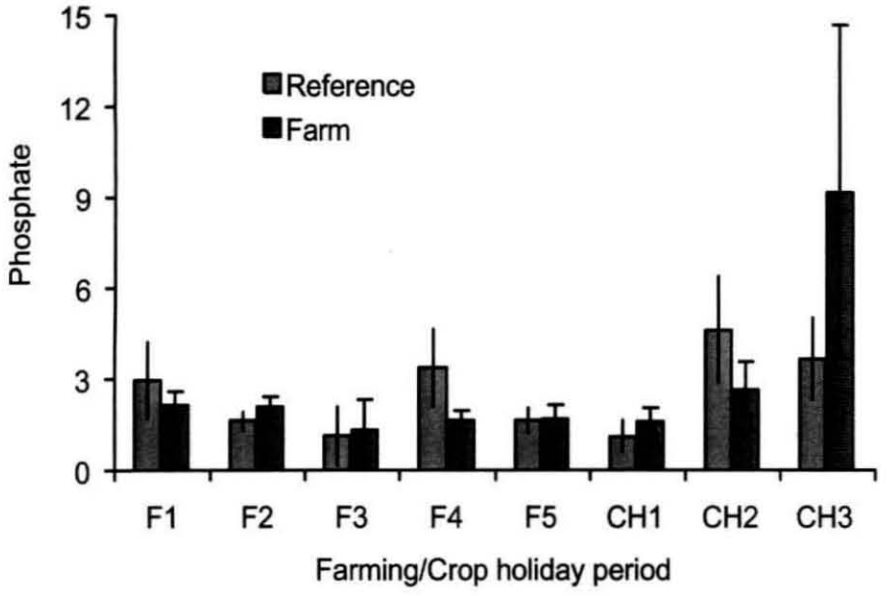

Figure 10. Mean values of phosphate at different farming and crop holiday period. Vertical bars indicate standard error

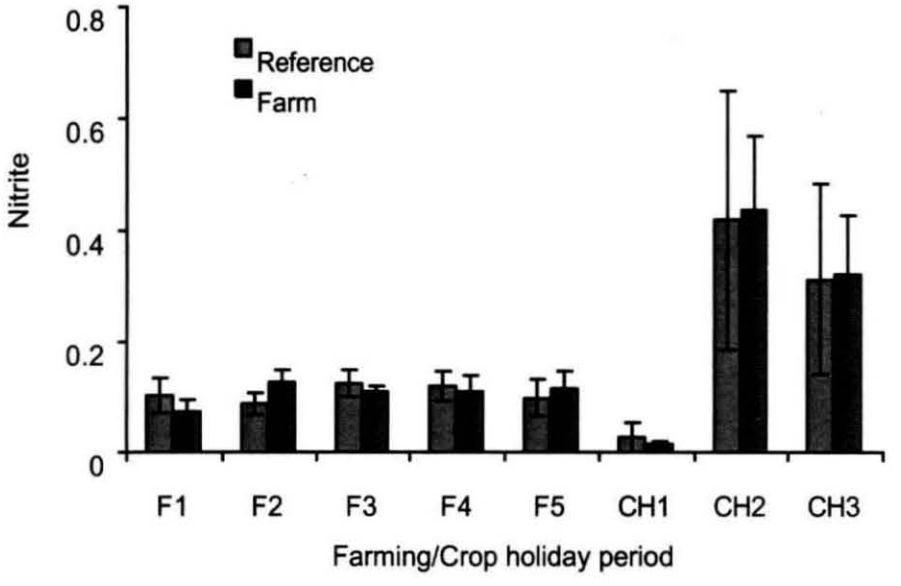

Figure 11. Mean values of nitrite at different farming and crop holiday period. Vertical bars indicate standard error

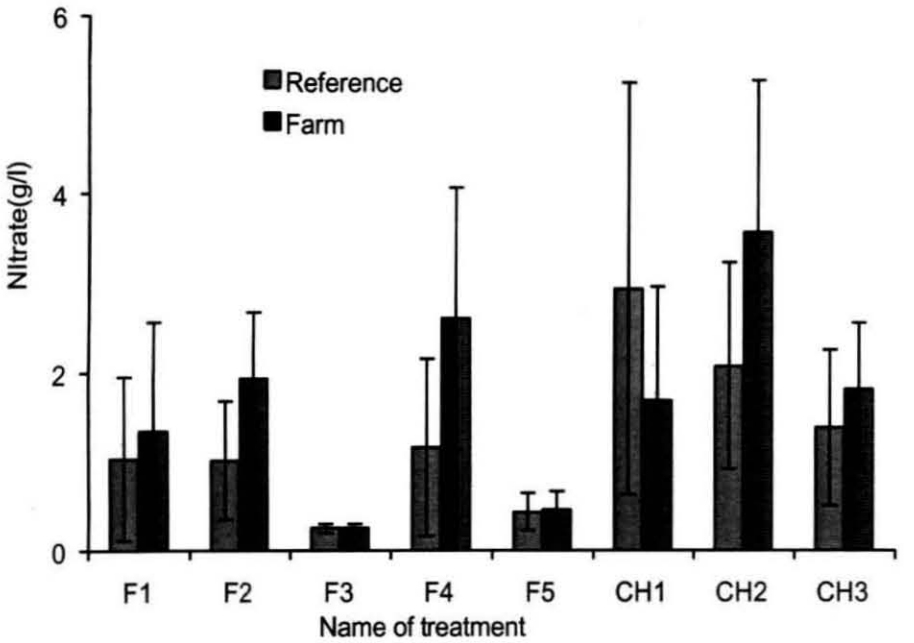

Figure 12. Mean values of nitrate at different sites of farming and crop holiday periods. Vertical bars indicate standard error

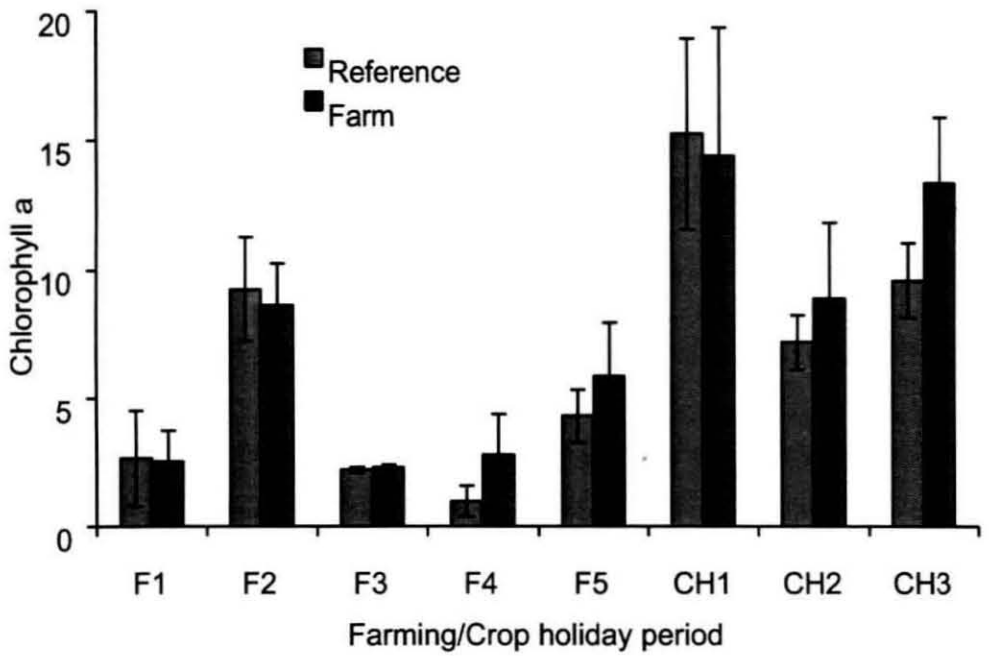

Figure 13. Mean values of Chlorophyll a content at different farming and crop holiday sites. Vertical bars indicate standard error

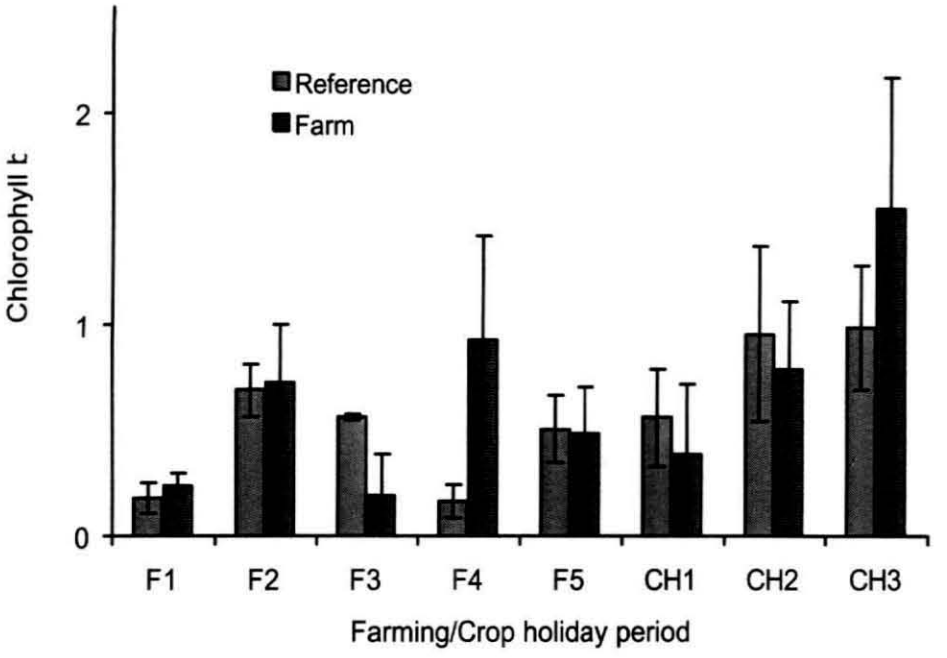

Figure 14. Mean values of Chlorophyll b content at different farming and crop holiday sites. Vertical bars indicate standard error

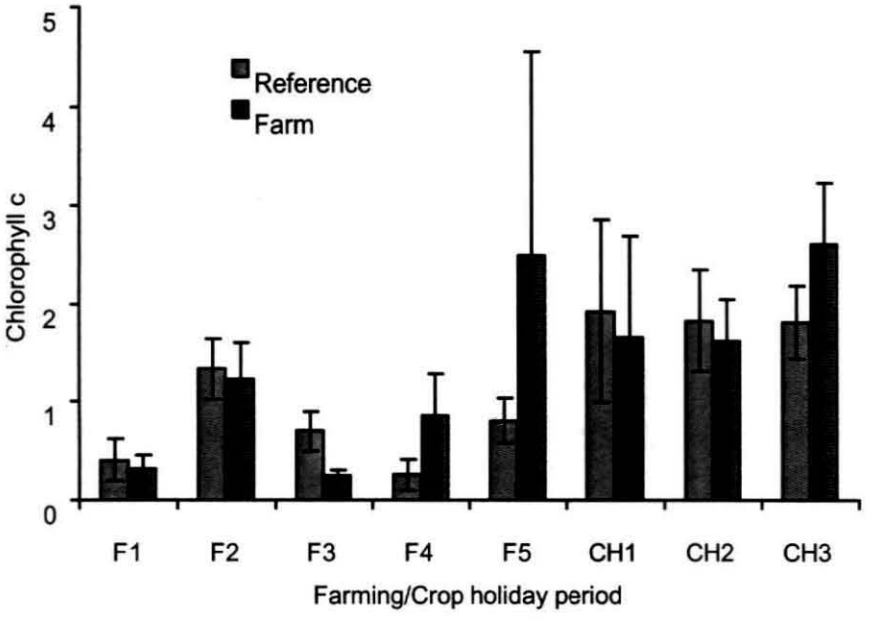

Figure 15. Mean values of Chlorophyll c content at different farming and crop holiday sites. Vertical bars indicate standard error

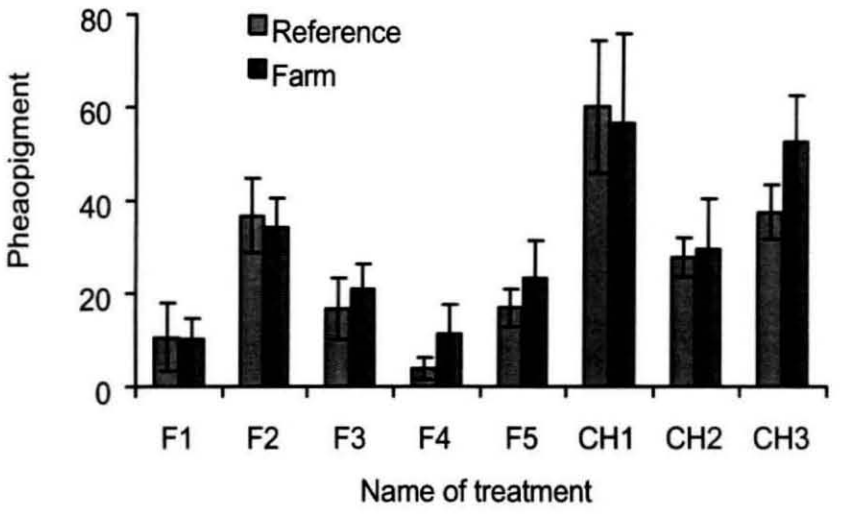

Figure 15. Mean values of phaeopigment content at different farming and crop holiday sites. Vertical bars indicate standard error

4.3 Impact assessment on sediment characteristics

The impact of oyster culture on sediment characteristics such as coarse sand, fine sand, silt, clay and organic carbon percentages in upper 5 cm and 5 – 10 cm sediment portions were assessed for various farming (F1, F2, F3, F4 & F5) and crop holiday (CH1, CH2 & CH3) periods; and the monthly variations are given in Tables 13 to 20. The mean percentages of various sediment characteristics of farm and reference sites of different farming and crop holiday periods are depicted in Figures 17 to 21.

4.3.1 Coarse sand

Percentage of coarse sand in the upper 5 cm portion of the farm substrate showed wide fluctuations during each farming period. Similar variations were observed at the reference sites also. The coarse sand fraction (%) ranged from 0.32 in Jan 2002 to 3.23 in Sep 2002 in F1 farm site, from 0.96 to 1.54 in F2 farm site, from 0.60 to 1.24 in F3 farm site, from 1.18 to 3.52 in F4 farm site and from 0.49 to 1.06 in F5 farm site. Similar seasonal variations were observed in the corresponding reference sites (Tables 13 to 20). Wide seasonal variations were not observed for sites under crop holiday periods.

The mean percentage coarse sand in upper 5 cm portion of the sediment of reference site was higher when compared to farm sites. Maximum coarse sand fraction (9.78%) was recorded from reference site of F4 and minimum (0.75%) from the farm site of F5. In general the coarse sand fraction (%) was found to decrease with the increasing period of farming (1.66 ± 0.28 for F1 and 0.75 ± 0.08 for F5). Exceptionally high values of 2.53 ± 0.42 for farm site and 9.30 ± 4.27 for reference site were recorded for F4. Coarse sand fraction of sites under crop holiday was also found to decrease from 2.80 ± 0.30 for farm site and 2.29 ± 0.34 for reference site of CH1 to 0.76 ± 0.12 for farm site and 1.32 ± 0.15 for reference site of CH3. Coarse sand fractions for CH2 were almost similar (Fig. 17a).

Percentage coarse sand fraction in the 5 to 10 cm portion of the sediment of the farm site during the study period ranged from 0.49 to 5.49 at F1, 0.72 to 1.52 at F2, 0.78 to 0.94 at F4 and 1.68 to 4.47 at F5; the range of corresponding variations at

the reference sites were 0.80 to 32.62, 1.10 to 2.37, 0.80 to 32.62 and 1.10 to 1.43 respectively (Tables 13 to 17). Wide seasonal variations were not observed for sites under crop holiday periods (Tables 18 to 20).

The mean percentage coarse sand in 5 – 10 cm portion of sediment was higher for reference sites when compared to the 5 -10 cm portion of farm site as well as upper 5 cm portion of reference site. Whereas the coarse sand fraction of farm sites except F1 & F4 was less when compared to that of upper 5 cm portion of sediment. Mean coarse sand values for farm sites F1, F2, F3, F4 & F5 were 1.81 ± 0.50, 1.06 ± 0.07, 0.86 ± 0.08, 3.23 ± 0.45 & 0.70 ± 0.06 with the corresponding reference site values of 7.15 ± 3.81, 1.48 ± 0.13, 1.63 ± 0.16, 9.78 ± 5.66, & 1.22 ± 0.06 respectively. Mean coarse sand values for CH1, CH2 & CH3 were found to be 65.65 ± 3.32, 66.75 ± 4.24 & 58.41 ± 2.15 for farm sites and 2.12 ± 0.24, 1.07 ± 0.12 & 1.25 ± 0.14 for the reference sites respectively (Fig. 18b)

Coarse sand fractions of F1 were significantly different ($F = 10.81$, $p<0.001$, Table 21) from F2 & F5 and that of F4 significantly differed from F2, F3 & F5. Significant ($F = 4$, $p<0.001$) differences in coarse sand fractions were observed between farm and reference sites of F1 & F4. Year of farming had no effect on variations of coarse sand from different portions of sediment. The coarse sand fraction of CH2 significantly ($F = 43.80$, $p<0.001$) differed from CH1 & CH3. No significant differences between the portions of sediment within any crop holiday period were observed (Table 22).

4.3.2 Fine sand

Percentage of fine sand in the upper 5 cm portion of the farm substrate showed wide fluctuations during each farming period. Similar variations were observed at the reference sites also. The fine sand fraction (%) ranged from 66.07 in Jan 2002 to 76.78 in May 2002 in F1 farm site, from 46.05 to 78.58 in F2 farm site, from 55.25 to 75.05 in F4 farm site and from 48.47 to 65.78 in F5 farm site. Similar seasonal variations were observed in the corresponding reference sites also (Table 13 to 20). Fine sand values for sites under crop holiday periods were generally lower when compared to farming periods.

The mean percentage fine sand in upper 5 cm portion of the sediment of reference site was higher when compared to farm sites. Maximum fine sand fraction (78.58%) was recorded from reference site of F2 and minimum (48.47%) from the farm site of F5. In general the fine sand fraction (%) was found to decrease with the increasing period of farming (72.11 ± 1.38 for F1 and 57.08 ± 2.44 for F5). Exceptional values of 70.08 ± 2.11, and 68.71 ± 2.89 were recorded from farm sites of F3 & F4. Fine sand fraction of sites under crop holiday was also found to decrease from 67.77 ± 3.71 for farm site and 75.84 ± 0.50 for reference site of CH1 to 49.45 ± 4.32 for farm site and 71.66 ± 2.23 for reference site of CH3 (Fig. 18a).

Percentage fine sand fraction in the 5 to 10 cm portion of the sediment of the farm site during the study period ranged from 61.65 to 74.63 at F1, 62.68 to 79.01 at F2, 61.12 to 69.94 at F4 and 48.99 to 65.21 at F5; the range of corresponding variations at the reference sites were 56.22 to 76.95, 67.30 to 78.77, 56.22 to 76.95 and 67.30 to 78.77 respectively (Tables 13 to 17). Seasonal variations were also prominent at the sites under crop holiday periods (Tables 18 to 20).

The mean percentage fine sand in 5 – 10 cm portion of sediment was generally higher for reference sites when compared to the 5 -10 cm portion of farm site as well as reference site of upper 5 cm portion. Whereas the fine sand fraction of farm sites except F1 & F4 was less when compared to that of upper 5 cm portion of sediment. Mean fine sand values for farm sites F1, F2, F3, F4 & F5 were 69.76 ± 1.51, 72.67 ± 1.83, 67.67 ± 5.54, 66.86 ± 1.76 & 58.26 ± 2.4 with the corresponding reference site values of 70.31 ± 2.57, 72.19 ± 1.30, 72.41 ± 0.87, 68.05 ± 3.47, & 72.06 ± 2.16 respectively. Mean fine sand values of CH1, CH2 & CH3 were found to be 4.10 ± 1.59, 0.94 ± 0.08 & 0.98 ± 0.30 for farm sites and 72.92 ± 3.55, 72.14 ± 2.55 & 72.83 ± 1.70 for the reference sites respectively (Fig. 18b)

Fine sand fractions of F1 were significantly different ($F = 7.21$, $p<0.001$, Table 21) from F5 and that of F2 significantly differed from F5, & F4. Significant ($F = 7.53$, $p<0.001$) differences in fine sand fractions were observed between farm and reference sites of F5, and between upper portions of F1 & F2 sediment (Table 21). Year of farming had no effect on variations of fine sand from different portions of sediment within the farming period ($F = 0.81$, $p>0.05$). The fine sand fraction of CH3 significantly ($F = 7.74$, $p<0.0001$) differed from CH1 & CH2. No significant differences

between the portions of sediment within any crop holiday period were observed (Table 22).

4.3.3 Silt

Percentage of silt in the upper 5 cm portion of the farm substrate showed wide fluctuations during each farming period. Similar variations were observed at the reference sites also. The silt fraction (%) ranged from 9.10 to 15.00 in F1 farm site, from 2.13 to 30.82 in F2 farm site, from 13.40 to 16.91 in F3 farm site, from 10.25 to 23.14 in F4 farm site and from 11.03 to 22.46 in F5 farm site. Similar seasonal variations were observed in the corresponding reference sites also (Tables 13 to 17). Highest seasonal variations in percentage silt fraction were recorded from sites under crop holiday periods (Tables 18 to 20).

The mean percentage silt in upper 5 cm portion of the sediment of farm site was higher when compared to the corresponding reference sites. Maximum silt fraction (17.35%) was recorded from farm site of F5 and minimum (7.75%) from the reference site of F2. In general the silt fraction (%) was found to increase with the increasing period of farming (12.34 ± 0.70 for F1 and 17.35 ± 1.90 for F5). Exceptional values of 15.16 ± 1.78, and 15.62 ± 1.51 were recorded from farm and reference sites of F3. Silt fraction of sites under crop holiday was also found to increase from 15.57 ± 3.94 for farm site of CH1 to 23.83 ± 4.03 for farm site of CH3. The mean silt values of reference sites under crop holiday periods more or less remained constant through out the study period (Fig. 19a).

Percentage silt fraction in the 5 to 10 cm portion of the sediment of the farm site during the study period ranged from 7.98 to 15.40 at F1, 3.17 to 16.86 at F2, 14.06 to 18.89 at F3, 7.10 to 19.96 at F4 and 9.22 to 25.96 at F5; the range of corresponding variations at the reference sites were 0.77 to 16.12, 1.23 to 12.92, 9.14 to 16.12, 0.77 to 13.33 and 1.23 to 11.65 respectively (Tables 13 to 17). Seasonal variations were also prominent at the sites under crop holiday periods (Tables 18 to 20).

The mean percentage silt in 5 – 10 cm portion of sediment was generally lower for farm sites when compared upper 5 cm portion. The same trend was

observed for reference sites also and the reference site values were generally lower when compared to the farm sites. The differences of mean silt percentages of farm and reference sites under crop holiday periods were very distinct and the values of reference sites were lower when compared to the farm sites. Mean silt values for farm sites F1, F2, F3, F4 & F5 were 12.42 ± 0.85, 8.46 ± 1.28, 16.47 ± 2.44, 14.79 ± 2.09, & 15.85 ± 2.66 with the corresponding reference site values of 9.22 ± 1.40, 6.95 ± 1.15, 12.63 ± 3.53, 8.47 ± 1.72, & 6.19 ± 1.56 respectively. Mean silt values of CH1, CH2 & CH3 were found to be 14.87 ± 0.79, 12.72 ± 3.65, & 16.02 ± 1.81 for farm sites and 9.80 ± 1.76, 6.94 ± 1.58, & 6.48 ± 1.14 for the reference sites respectively (Fig. 19b)

Silt fractions of F3 were significantly different ($F = 435.46$, $p<0.001$, Table 21) from F1, F2, F5 and that of F5 significantly differed from F1, F2 & F4. Significant ($F = 7.53$, $p<0.001$) differences in silt fractions were observed between farm and reference sites of F4 and F5, and between upper portion of F2 and 5 – 10 cm portion of F1 sediment (Table 21). Year of farming had no effect on variations of silt from different portions of sediment within the farming period ($F = 1.72$, $p>0.05$). The silt fraction of CH3 significantly ($F = 3.0$, $p<0.05$) differed from CH1. No significant differences between the portions of sediment within any crop holiday period were observed (Table 22).

4.3. 4 Clay

Percentage of clay in the upper 5 cm portion of the farm substrate showed wide fluctuations during each farming period. Similar variations were observed at the reference sites also. The clay fraction (%) ranged from 7.08 to 17.7 in F1 farm site, from 10.82 to 24.22 in F2 farm site, from 9.50 to 15.82 in F4 farm site and from 13.87 to 26.00 in F5 farm site. Similar seasonal variations were observed in the corresponding reference sites also (Tables 13 to 17). Wide seasonal variations of percentage clay fraction were recorded from sites under crop holiday periods (Tables 18 to 20).

The mean percentage clay in upper 5 cm portion of the sediment of farm site was higher when compared to the corresponding reference sites. Maximum clay fraction (20.00%) was recorded from farm site of F5 and minimum (11.20%) from the

reference site of F1. In general the clay fraction (%) was found to increase with the increasing period of farming (11.32 ± 1.10 for F1 and 20.00 ± 1.68 for F5). Clay fraction of sites under crop holiday was also found to increase from 11.96 ± 0.94 for farm site of CH1 to 23.39 ± 1.09 for farm site of CH3. The mean clay values of reference sites of CH2 and CH3 more or less remained constant through out the study period (Fig. 20a).

Percentage clay fraction in the 5 to 10 cm portion of the sediment of the farm site during the study period ranged from 5.61 to 22.30 at F1, 9.58 to 18.35 at F2, 6.28 to 22.28 at F4 and 19.68 to 26.92 at F5; the range of corresponding variations at the reference sites were 6.21 to 11.98, 8.75 to 18.51, 6.21 to 15.17 and 12.54 to 16.65 respectively (Table 13 to 17). Seasonal variations were minimal at the sites under crop holiday periods (Table 18 to 20).

The mean percentage clay in 5 – 10 cm portion of sediment was generally lower for farm sites when compared to upper 5 cm portion. The same trend was observed for reference sites also and the reference site values were generally lower when compared to the farm sites. The differences of mean clay percentages of farm and reference sites under crop holiday periods were very distinct and the values of reference sites were lower when compared to the farm site values. Mean clay values for farm sites F1, F2, F3, F4 & F5 were 11.95 ± 1.62, 14.93 ± 0.95, 13.24 ± 1.64, 12.02 ± 2.45, & 22.73 ± 1.21 with the corresponding reference site values of 10.16 ± 0.87, 14.13 ± 0.89, 10.82 ± 0.43, 10.10 ± 1.35, & 14.79 ± 0.61 respectively. Mean clay values of CH1, CH2 & CH3 were found to be 12.73 ± 1.19, 17.37 ± 0.95, & 21.57 ± 0.71 for farm sites and 9.29 ± 0.35, 14.41 ± 0.92, & 14.93 ± 0.76 for the reference sites respectively (Fig. 20b)

Clay fractions of F5 were significantly different ($F = 31.14$, $p<0.0001$, Table 21) from F1, F2, F3, F4 and that of F2 significantly differed from F4, & F5. Significant ($F = 4.3$, $p<0.0001$) differences in clay fractions were observed between farm and reference sites for F5 in 5 – 10 cm sediment (Table 21). Year of farming had no effect on variations of clay from different portions of sediment within the farming period ($F = 0.06$, $p>0.05$). The clay fraction of CH1 significantly ($F = 46.96$, $p<0.0001$) differed from CH2 & CH3. No significant differences between the portions of sediment within any crop holiday period were observed (Table 22).

4.3.5 Organic carbon

Percentage of organic carbon in the upper 5 cm portion of the farm substrate unlike particle size composition did not vary much during each farming period. The organic carbon percentage ranged from 0. 64 to 1.03 in F1 farm site, from 0.72 to 1.35 in F2 farm site, from 0.86 to 1.55 in F4 farm site and from 0.77 to 1.60 in F5 farm site. Variations observed in the corresponding reference sites were 0.24 to 1.11, 0.24 to 0.82, 0.24 to 1.41, and 0.24 to 0.87 respectively (Tables 13 to 17). Seasonal variations in percentage organic carbon were also recorded from sites under crop holiday periods (Tables 18 to 20).

The mean percentage organic carbon in upper 5 cm portion of the sediment of farm site was higher when compared to the corresponding reference sites. Maximum organic carbon content (1.24%) was recorded from farm site of F5 and minimum (0.73%) from the reference site of F1. In general the organic carbon content (%) was found to increase with the increasing period of farming (0.87 ± 0.04 for F1 and 1.24 ± 0.13 for F5). Organic carbon content of sites under crop holiday was also found to increase from 1.15 ± 0.10 for farm site of CH1 to 1.59 ± 0.12 for farm site of CH3. The mean organic carbon values of reference sites of CH2 and CH3 more or less remained constant through out the study period (Fig. 21a).

Percentage organic carbon content in the 5 to 10 cm portion of the sediment of the farm site during the study period ranged from 0.45 to 1.00 at F1, 0.46 to 1.16 at F2, 0.69 to 1.29 at F4 and 0.68 to 1.45 at F5; the range of corresponding variations at the reference sites were 0.18 to 1.03, 0.32 to 0.78, 0.20 to 1.03 and 0.32 to 0.77 respectively (Tables 13 to 17). Seasonal variations in percentage organic carbon were minimal at the sites under crop holiday periods (Tables 18 to 20).

The mean percentage organic carbon in 5 – 10 cm portion of sediment was generally lower for farm sites when compared to upper 5 cm portion. The same trend was observed for reference sites also and the reference site values were generally lower when compared to the farm sites. The differences of mean organic carbon percentages of farm and reference sites under crop holiday periods were very distinct and the values of reference sites were lower when compared to the farm site values. Mean organic carbon values for farm sites F1, F2, F3, F4 & F5 were 0.73 ± 0.06,

0.80 ± 0.07, 0.93 ± 0.24, 0.95 ± 0.09, & 1.09 ± 0.13 with the corresponding reference site values of 0.59 ± 0.09, 0.59 ± 0.09, 0.71 ± 0.12, 0.51 ± 0.13, & 0.56 ± 0.07 respectively. Mean organic carbon values of CH1, CH2 & CH3 were found to be 1.09 ± 0.17, 0.81 ± 0.10, & 1.18 ± 0.05 for farm sites and 0.71 ± 0.09, 0.50 ± 0.11, & 0.52 ± 0.08 for the reference sites respectively (Fig. 21b)

Percentage organic carbon of F1 were significantly different ($F = 2.58$, $p<0.05$, Table 21) from F5. Significant ($F = 11.04$, $p<0.0001$) differences in organic carbon values were observed between farm and reference sites of F2, F4 & F5 (Table 21). Organic carbon values of up to 5 cm and 5-10 cm portions of sediment in all the years of farming significantly differed ($F = 12.44$, $p<0.005$). The organic carbon values of CH1 significantly ($F = 8.32$, $p<0.001$) differed from CH3. Portion of sediment also differed in all the crop holiday periods ($F= 12.53$ $p<0.001$). The differences of farm and reference sites under crop holiday periods were also significant ($F = 28.66$, $p<0.0001$) (Table 22).

Table 13 Sediment characteristics for farm and reference sites of one year farming period (F1)

			Month								
Characteristic	Site	Portion of sediment	Jan'02	Feb'02	Mar'02	Apr'02	May'02	Jun'02	Jul'02	Aug'02	Sep'02
% Coarse sand	Farm	upper 5 cm	0.32	1.52	0.95	2.06	1.25	2.45	1.83	1.34	3.23
		5-10 cm	0.49	1.33	1.11	1.89	1.61	1.30	2.34	0.70	5.49
	Reference	upper 5 cm	1.00	1.16	1.33	15.66	1.88	26.82	8.52	1.62	2.80
		5-10 cm	1.79	1.47	0.80	20.56	0.94	32.62	2.36	1.42	2.36
% Fine sand	Farm	upper 5 cm	66.07	72.05	71.74	76.63	76.78	67.70	74.29	67.72	76.04
		5-10 cm	61.65	73.92	71.97	74.63	71.13	71.88	71.38	67.87	63.36
	Reference	upper 5 cm	69.61	71.08	62.00	65.44	73.41	59.47	57.34	75.07	74.89
		5-10 cm	73.27	71.56	67.42	60.76	76.95	56.22	70.73	76.24	79.66
% Silt	Farm	upper 5 cm	13.41	12.98	15.00	12.72	9.40	10.97	12.85	14.65	9.10
		5-10 cm	15.40	12.69	10.78	15.37	10.44	7.89	11.10	13.46	14.65
	Reference	upper 5 cm	17.11	14.12	13.27	5.93	8.88	3.81	8.55	10.40	8.08
		5-10 cm	9.14	16.12	8.88	9.61	9.38	0.77	13.33	8.87	6.84
% Clay	Farm	upper 5 cm	17.70	12.73	12.02	7.08	9.73	13.25	7.67	12.64	9.02
		5-10 cm	22.30	10.21	8.68	5.61	9.51	15.51	9.94	13.96	11.81
	Reference	upper 5 cm	9.81	12.80	15.10	8.17	8.16	8.32	19.93	9.39	9.17
		5-10 cm	11.25	10.39	15.17	6.21	10.91	8.04	11.98	8.32	9.18
% Organic carbon	Farm	upper 5 cm	0.90	0.64	0.88	0.98	0.88	0.77	0.74	1.03	1.00
		5-10 cm	0.79	0.52	0.45	0.76	0.78	0.51	1.00	0.86	0.92
	Reference	upper 5 cm	1.08	0.75	0.71	0.54	0.70	0.24	1.41	0.48	1.11
		5-10 cm	0.83	0.60	0.52	0.20	0.61	0.18	1.03	0.51	0.83

Table 14 Sediment characteristics for farm and reference sites of two year farming period (F2)

Characteristic	Site	Portion of sediment	Month										
			Oct'02	Sep'02	Oct'02	Nov'02	Dec'02	Jan'03	Feb'03	Mar'03	Apr'03	May'03	Jun'03
% Coarse sand	Farm	upper 5 cm	1.47	1.78	0.96	1.27	1.26	1.00	1.12	1.18	1.54	1.20	0.97
		5-10 cm	1.32	1.52	0.72	1.11	0.81	1.19	1.13	0.88	1.01	1.14	0.86
	Reference	upper 5 cm	1.65	2.43	1.00	1.17	1.55	1.61	1.65	1.22	1.51	2.10	1.22
		5-10 cm	1.65	2.37	1.14	1.27	1.10	1.43	1.30	1.10	1.41	2.10	1.36
% Fine sand	Farm	upper 5 cm	74.36	71.80	75.49	78.58	67.05	65.21	68.81	68.39	46.05	49.44	50.47
		5-10 cm	76.16	74.23	76.77	78.82	76.95	73.37	79.01	62.68	70.72	64.29	66.39
	Reference	upper 5 cm	76.55	76.10	76.82	77.38	74.23	66.83	72.83	63.29	72.36	72.69	75.10
		5-10 cm	71.50	67.61	78.77	77.89	67.30	67.54	72.32	68.52	73.69	76.01	72.96
% Silt	Farm	upper 5 cm	7.36	6.79	7.26	2.13	15.31	16.76	8.92	12.59	30.82	23.83	20.37
		5-10 cm	7.61	9.02	5.30	3.17	5.03	7.62	5.22	16.86	8.14	11.89	13.16
	Reference	upper 5 cm	9.08	8.37	5.04	2.36	4.93	13.39	5.48	15.42	8.48	8.31	4.42
		5-10 cm	9.64	12.92	5.21	1.23	5.45	9.41	4.19	11.65	8.57	4.40	3.74
% Clay	Farm	upper 5 cm	12.20	10.82	13.94	14.15	15.62	14.08	13.41	17.15	20.67	24.22	20.68
		5-10 cm	10.05	9.58	15.12	15.43	17.10	14.02	12.71	16.75	17.34	17.80	18.35
	Reference	upper 5 cm	9.55	8.40	13.19	17.31	14.21	16.33	13.47	17.65	15.79	13.21	14.70
		5-10 cm	8.75	9.95	12.54	13.91	14.63	15.89	15.14	16.65	14.06	15.40	18.51
% Organic carbon	Farm	upper 5 cm	0.80	0.91	0.75	0.72	1.06	1.25	0.82	1.02	1.28	1.20	1.35
		5-10 cm	0.53	0.71	0.46	0.61	0.90	0.93	0.81	1.02	0.67	1.16	1.03
	Reference	upper 5 cm	0.53	0.71	0.24	0.54	0.73	0.82	0.80	0.87	0.72	0.68	0.72
		5-10 cm	0.53	0.78	0.32	0.40	0.63	0.70	0.77	0.56	0.49	0.67	0.55

Table 15 Sediment characteristics for farm and reference sites of three year farming period (F3)

Characteristic	Site	Portion of sediment	Month	
			Jan'02	Feb'02
% Coarse sand	Farm	upper 5 cm	0.60	1.24
		5-10 cm	0.78	0.94
	Reference	upper 5 cm	1.00	1.16
		5-10 cm	1.79	1.47
% Fine sand	Farm	upper 5 cm	67.99	72.17
		5-10 cm	62.19	73.16
	Reference	upper 5 cm	69.61	71.08
		5-10 cm	73.27	71.56
% Silt	Farm	upper 5 cm	13.40	16.91
		5-10 cm	18.89	14.06
	Reference	upper 5 cm	17.11	14.12
		5-10 cm	9.14	16.12
% Clay	Farm	upper 5 cm	16.34	9.29
		5-10 cm	14.86	11.62
	Reference	upper 5 cm	9.81	12.80
		5-10 cm	11.25	10.39
% Organic carbon	Farm	upper 5 cm	0.84	0.84
		5-10 cm	1.17	0.69
	Reference	upper 5 cm	1.08	0.75
		5-10 cm	0.83	0.60

Table 16 Sediment characteristics for farm and reference sites of four year farming period (F4)

Characteristic	Site	Portion of sediment	Month					
			Mar'02	Apr'02	May'02	Jun'02	Jul'02	Aug'02
% Coarse sand	Farm	upper 5 cm	1.18	2.65	3.52	1.51	3.54	2.81
		5-10 cm	1.68	3.88	4.01	2.90	4.47	2.43
	Reference	upper 5 cm	1.33	15.66	1.88	26.82	8.52	1.62
		5-10 cm	0.80	20.56	0.94	32.62	2.36	1.42
% Fine sand	Farm	upper 5 cm	68.57	70.66	75.05	70.72	72.01	55.25
		5-10 cm	63.30	68.17	72.48	66.13	69.94	61.12
	Reference	upper 5 cm	62.00	65.44	73.41	59.47	57.34	75.07
		5-10 cm	67.42	60.76	76.95	56.22	70.73	76.24
% Silt	Farm	upper 5 cm	15.29	15.68	11.61	10.91	10.25	23.14
		5-10 cm	16.94	19.72	12.99	7.10	12.03	19.96
	Reference	upper 5 cm	13.27	5.93	8.88	3.81	8.55	10.40
		5-10 cm	8.88	9.61	9.38	0.77	13.33	8.87
% Clay	Farm	upper 5 cm	13.17	9.88	9.50	15.82	12.46	15.03
		5-10 cm	12.62	6.28	8.90	22.28	7.68	14.35
	Reference	upper 5 cm	15.10	8.17	8.16	8.32	19.93	9.39
		5-10 cm	15.17	6.21	10.91	8.04	11.98	8.32
% Organic carbon	Farm	upper 5 cm	1.55	1.01	0.86	0.89	1.52	1.33
		5-10 cm	1.01	0.69	0.83	0.88	1.01	1.29
	Reference	upper 5 cm	0.71	0.54	0.70	0.24	1.41	0.48
		5-10 cm	0.52	0.20	0.61	0.18	1.03	0.51

Table 17 Sediment characteristics for farm and reference sites of five year farming period (F5)

Characteristic	Site	Portion of sediment	Month					
			Dec'02	Jan'03	Feb'03	Mar'03	Apr'03	May'03
% Coarse sand	Farm	upper 5 cm	1.06	0.49	0.76	0.78	0.70	0.72
		5-10 cm	0.57	0.56	0.89	0.64	0.67	0.84
	Reference	upper 5 cm	1.00	1.17	1.55	1.61	1.65	1.22
		5-10 cm	1.14	1.27	1.10	1.43	1.30	1.10
% Fine sand	Farm	upper 5 cm	65.78	57.13	56.38	60.58	54.17	48.47
		5-10 cm	65.21	63.76	56.16	57.31	58.12	48.99
	Reference	upper 5 cm	76.82	77.38	74.23	66.83	72.83	63.29
		5-10 cm	78.77	77.89	67.30	67.54	72.32	68.52
% Silt	Farm	upper 5 cm	14.56	11.03	22.46	18.42	15.33	22.31
		5-10 cm	11.14	9.22	15.05	20.95	12.76	25.96
	Reference	upper 5 cm	5.04	2.36	4.93	13.39	5.48	15.42
		5-10 cm	5.21	1.23	5.46	9.41	4.19	11.65
% Clay	Farm	upper 5 cm	13.87	26.00	18.98	18.69	22.28	20.18
		5-10 cm	19.68	23.76	26.92	19.12	23.50	23.38
	Reference	upper 5 cm	13.19	17.31	14.21	16.33	13.47	17.65
		5-10 cm	12.54	13.91	14.63	15.89	15.14	16.65
% Organic carbon	Farm	upper 5 cm	0.77	1.03	1.24	1.44	1.37	1.60
		5-10 cm	0.68	0.71	1.23	1.26	1.18	1.45
	Reference	upper 5 cm	0.24	0.54	0.73	0.82	0.80	0.87
		5-10 cm	0.32	0.40	0.63	0.70	0.77	0.56

Table 18 Sediment characteristics for crop holiday and reference sites of three month crop holiday period (CH1)

Characteristic	Site	Portion of sediment	Month		
			Sep'02	Oct'02	Nov'02
% Coarse sand	Farm	upper 5 cm	3.40	2.50	2.49
		5-10 cm	7.10	1.67	3.54
	Reference	upper 5 cm	2.80	1.65	2.43
		5-10 cm	2.36	1.65	2.37
% Fine sand	Farm	upper 5 cm	67.64	74.25	61.41
		5-10 cm	61.75	72.25	62.94
	Reference	upper 5 cm	74.89	76.55	76.10
		5-10 cm	79.66	71.50	67.61
% Silt	Farm	upper 5 cm	14.12	9.59	23.00
		5-10 cm	16.34	13.64	14.62
	Reference	upper 5 cm	8.08	9.08	8.37
		5-10 cm	6.84	9.64	12.92
% Clay	Farm	upper 5 cm	13.67	10.45	11.75
		5-10 cm	12.13	11.04	15.01
	Reference	upper 5 cm	9.17	9.55	8.40
		5-10 cm	9.18	8.75	9.95
% Organic carbon	Farm	upper 5 cm	1.30	0.97	1.19
		5-10 cm	1.41	0.82	1.06
	Reference	upper 5 cm	1.11	0.53	0.71
		5-10 cm	0.83	0.53	0.78

Table 19 Sediment characteristics for crop holiday and reference sites of six months crop holiday period (CH2)

Characteristic	Site	Portion of sediment	Month					
			Sep'03	Oct'03	Nov'03	Dec'03	Jan'04	Feb'04
% Coarse sand	Farm	upper 5 cm	0.87	0.92	0.81	0.97	1.11	1.18
		5-10 cm	0.72	1.25	0.91	0.81	1.01	0.96
	Reference	upper 5 cm	1.72	1.58	1.17	0.64	0.90	1.09
		5-10 cm	1.32	1.36	0.93	0.87	0.65	1.28
% Fine sand	Farm	upper 5 cm	66.66	58.79	48.65	58.34	74.50	70.72
		5-10 cm	47.55	73.71	66.21	74.37	64.32	74.35
	Reference	upper 5 cm	74.96	71.30	80.10	55.56	70.47	72.40
		5-10 cm	75.33	72.60	76.14	71.33	60.20	77.22
% Silt	Farm	upper 5 cm	11.82	14.34	23.68	17.55	6.03	9.32
		5-10 cm	30.17	6.97	13.30	6.46	11.03	8.36
	Reference	upper 5 cm	5.62	5.40	5.35	15.16	8.23	6.18
		5-10 cm	5.75	4.78	3.69	6.55	14.56	6.31
% Clay	Farm	upper 5 cm	12.94	21.60	23.31	19.92	15.79	16.79
		5-10 cm	19.65	17.26	18.67	16.31	19.00	13.33
	Reference	upper 5 cm	14.53	14.51	12.74	20.36	14.84	15.63
		5-10 cm	13.11	12.94	12.46	15.70	18.41	13.82
% Organic carbon	Farm	upper 5 cm	1.19	1.23	1.62	1.30	0.70	0.74
		5-10 cm	1.13	0.84	0.90	0.86	0.78	0.35
	Reference	upper 5 cm	0.70	0.64	0.45	0.88	0.62	0.55
		5-10 cm	0.31	0.52	0.31	0.86	0.81	0.19

Table 20 Sediment characteristics for crop holiday and reference sites of nine months crop holiday period (CH3)

			Month								
Characteristic	Site	Portion of sediment	Jun'03	Jul'03	Aug'03	Sep'03	Oct'03	Nov'03	Dec'03	Jan'04	Feb'04
% Coarse sand	Farm	upper 5 cm	0.70	1.65	0.53	0.73	0.64	0.46	0.59	0.77	0.78
		5-10 cm	0.65	3.39	0.61	0.64	0.58	0.69	0.61	0.94	0.71
	Reference	upper 5 cm	1.51	2.10	1.22	1.72	1.58	1.17	0.64	0.90	1.09
		5-10 cm	1.41	2.10	1.36	1.32	1.36	0.93	0.87	0.65	1.28
% Fine sand	Farm	upper 5 cm	48.80	28.74	42.25	63.06	55.55	30.90	63.17	59.15	53.41
		5-10 cm	53.73	64.56	44.80	64.01	59.81	61.34	62.02	53.68	61.78
	Reference	upper 5 cm	72.36	72.69	75.10	74.96	71.30	80.10	55.56	70.47	72.40
		5-10 cm	73.69	76.01	72.96	75.33	72.60	76.14	71.33	60.20	77.22
% Silt	Farm	upper 5 cm	24.70	43.67	25.04	11.75	17.12	42.06	9.65	16.74	23.76
		5-10 cm	23.03	10.17	24.26	10.49	13.87	13.00	13.57	21.56	14.19
	Reference	upper 5 cm	8.48	8.31	4.42	5.62	5.40	5.35	15.16	8.23	6.18
		5-10 cm	8.57	4.40	3.74	5.75	4.78	3.69	6.55	14.56	6.31
% Clay	Farm	upper 5 cm	23.31	25.82	29.64	21.13	23.28	25.88	20.87	21.52	19.02
		5-10 cm	20.48	18.85	26.29	22.44	22.95	21.00	20.10	21.24	20.75
	Reference	upper 5 cm	15.79	13.21	14.70	14.53	14.51	12.74	20.36	14.84	15.63
		5-10 cm	14.06	15.40	18.51	13.11	12.94	12.46	15.70	18.41	13.82
% Organic carbon	Farm	upper 5 cm	1.46	1.79	1.63	1.61	1.93	2.22	1.06	1.11	1.48
		5-10 cm	1.06	1.01	1.38	1.29	1.32	1.29	1.17	1.16	0.97
	Reference	upper 5 cm	0.72	0.68	0.72	0.70	0.64	0.45	0.88	0.62	0.55
		5-10 cm	0.49	0.67	0.55	0.31	0.52	0.31	0.86	0.81	0.19

Table 21 ANOVA (Nested) and Tukey post hoc test results accomplished with the sediment characteristics between the sites and years of farming period

Variable	Source of Variability	F	P	Tukey post hoc test
Coarse sand	Between Year of farming	10.81	<0.001	F4 – F2, F3, F5 F1 – F2, F5
	Portion of sediment	0.06	*NS	
	Year of farming vs. portion of sediment	0.05	NS	
	Farm vs. Reference (within the year of farming)	4.00	<0.001	F1 (up to 5cm) F1 (5 to 10cm) F4 (up to 5cm) F4 (5 to 10cm)
Fine sand	Year of farming	7.21	<0.001	F2 – F4, F5, F4 F1 – F5
	Portion of sediment	0.81	NS	
	Year of farming vs. portion of sediment	0.75	NS	
	Farm vs. Reference (within the year of farming	7.53	<0.001	F1 (up to 5cm) F2 (up to 5 cm) F5 (up to 5cm) F5 (5 to 10cm)
Silt	Year of farming	435.46	<0.001	F3 – F1, F5, F2 F5 – F4, F1, F2
	Portion of sediment	1.72	NS	
	Year of farming vs. portion of sediment	1.13	NS	
	Farm vs. Reference (within the year of farming)	146.32	<0.05	F1 (5 to 10cm) F2 (up to 5cm) F4 (up to 5cm) F4 (5 to 10cm) F5 (up to 5cm) F5 (5 to 10cm)
Clay	Year of farming	31.14	0.0001	F5 – F1, F2, F3, F4 F2 – F4, F5 F1 – F2
	Portion of sediment	0.06	NS	
	Year of farming vs. portion of sediment	0.51	NS	
	Farm vs. Reference (within the year of farming)	4.30	<0.0001	F5 (5 to 10cm)
Organic carbon	Year of farming	2.58	<0.05	F1 – F5
	Portion of sediment	12.44	<0.005	up to 5cm 5 to 10cm
	Year of farming vs. portion of sediment	0.27	NS	
	Farm vs. Reference (within the year of farming)	11.04	<0.0001	F2 (up to 5m) F2 (5 to 10cm) F4 (up to 5cm) F4 (5 to 10cm) F5 (up to 5cm) F5 (5 to 10cm)

*NS = Not significant

Table 22 ANOVA (Nested) and Tukey post hoc test results accomplished with the sediment characteristics within and between the sites of crop holiday period

Variable	Source of Variability	F	P	Tukey post hoc test
Coarse sand	Between crop holiday period	43.80	<0.001	CH2 – CH1, CH3,
	Portion of sediment	1.50	NS	
	crop holiday period vs. portion of sediment	1.19	NS	
	Farm vs. Reference (within crop holiday period)	3.84	<0.001	CH2 (5 to 10cm) CH3 (top 5cm)
Fine sand	Between crop holiday period	7.74	<0.0001	CH2 – CH3 CH1 – CH3
	Portion of sediment	1.00	*NS	
	crop holiday period vs. portion of sediment	1.53	NS	
	Farm vs. Reference (within crop holiday period)	13.99	<0.001	CH1 (top 5cm) CH3 (top 5cm) CH3 (5 to 10cm)
Silt	Between crop holiday period	3	<0.05	CH3 – CH1
	Portion of sediment	1.69	NS	
	crop holiday period vs. portion of sediment	1.47	NS	
	Farm vs. Reference (within crop holiday period)	13.40	<0.001	CH1 (top 5cm) CH1 (5 to 10cm) CH3 (top 5cm) CH3 (5 to 10cm)
Clay	Between crop holiday period	46.96	<0.0001	CH1 – CH2, CH3 CH2 – CH3
	Portion of sediment	0.62	NS	
	crop holiday period vs. portion of sediment	0.48	NS	
	Farm vs. Reference (within crop holiday period)	15.87	<0.001	CH1 (top 5cm) CH1 (5 to 10cm) CH3 (top 5cm) CH3 (5 to 10cm)
Organic carbon	Between crop holiday period	8.32	<0.001	CH1 – CH3
	Portion of sediment	12.53	<0.001	
	crop holiday period vs. portion of sediment	1.14	NS	
	Farm vs. Reference (within crop holiday period)	28.66	<0.0001	CH1 (top 5cm) CH1 (5 to 10cm) CH2 (top 5cm) CH2 (5 to 10cm) CH3 (top 5cm) CH3 (5 to 10cm)

*NS = not significant

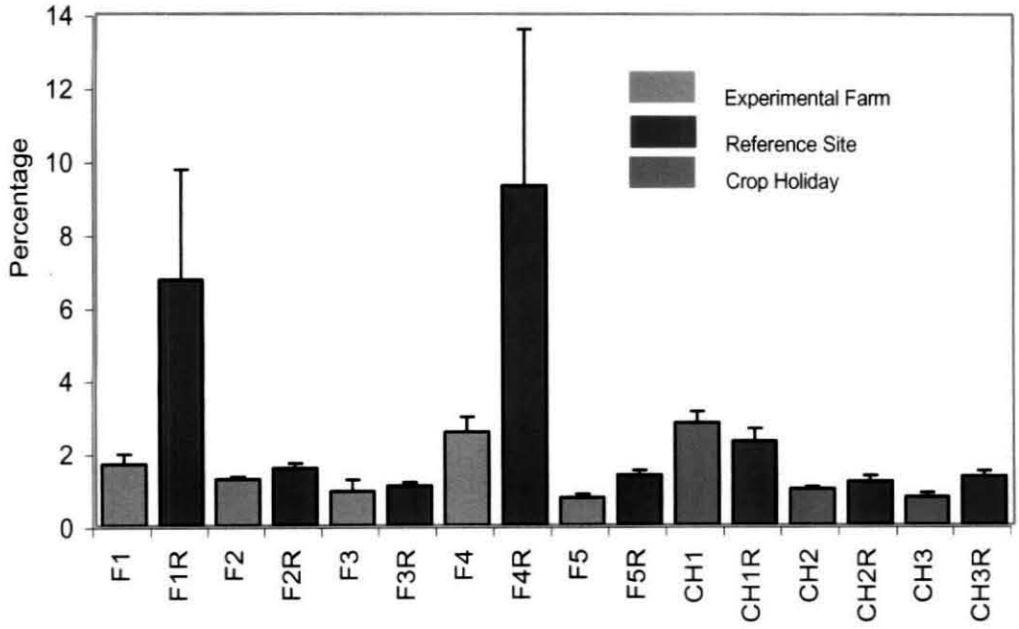

Figure 17a. Change in percentage coarse sand in upper 5 cm of sediment in different oyster farms. Vertical bars indicate standard error

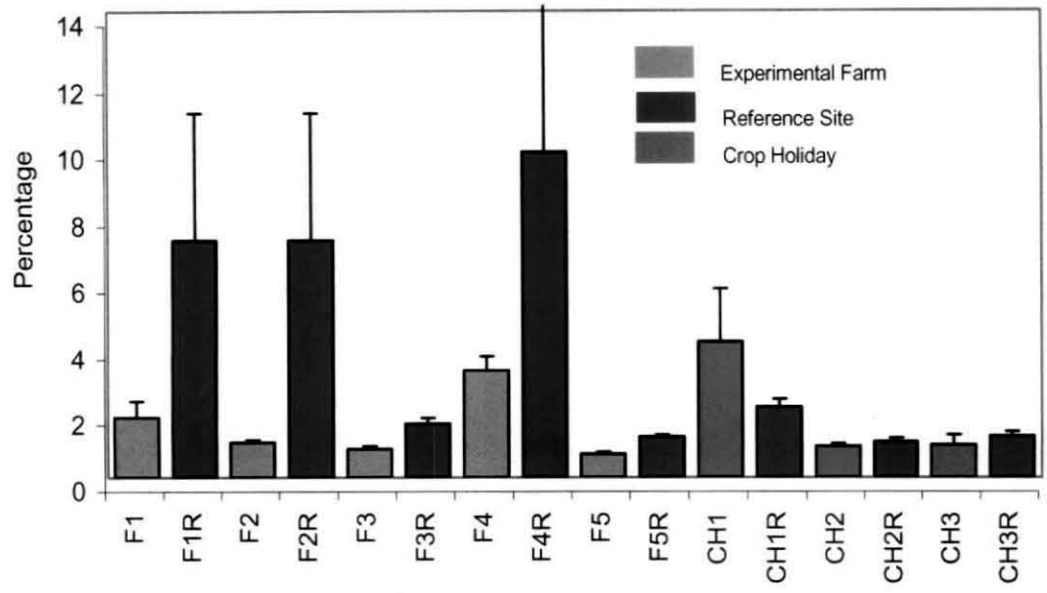

Figure 17b. Change in percentage coarse sand in 5-10 cm of sediment in different oyster farms. Vertical bars indicate standard error

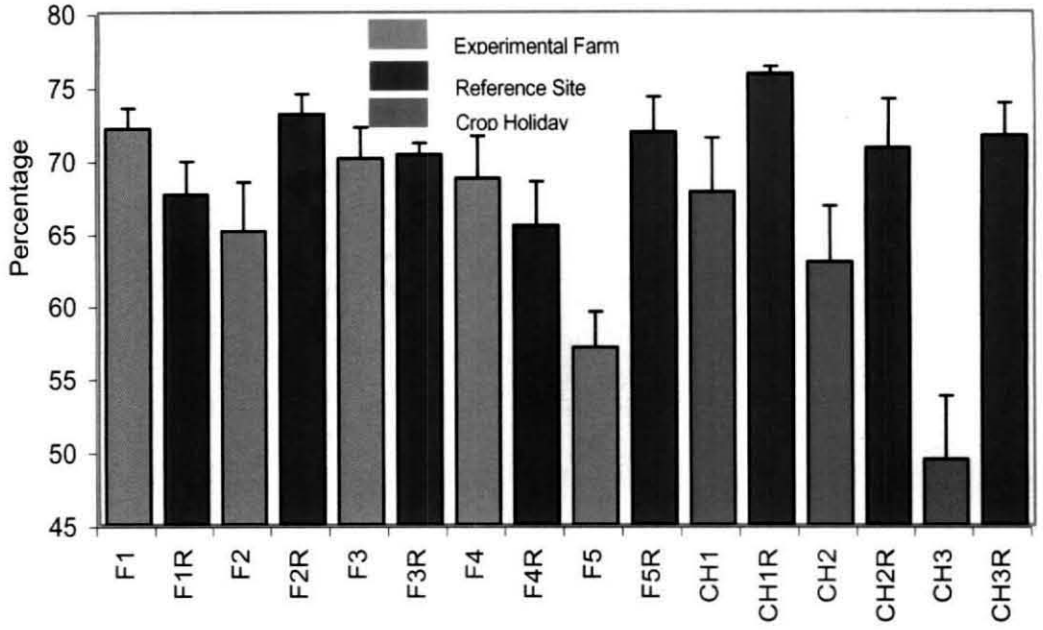

Figure 18a. Change in percentage fine sand in upper 5 cm of sediment in different oyster farms. Vertical bars indicate standard error

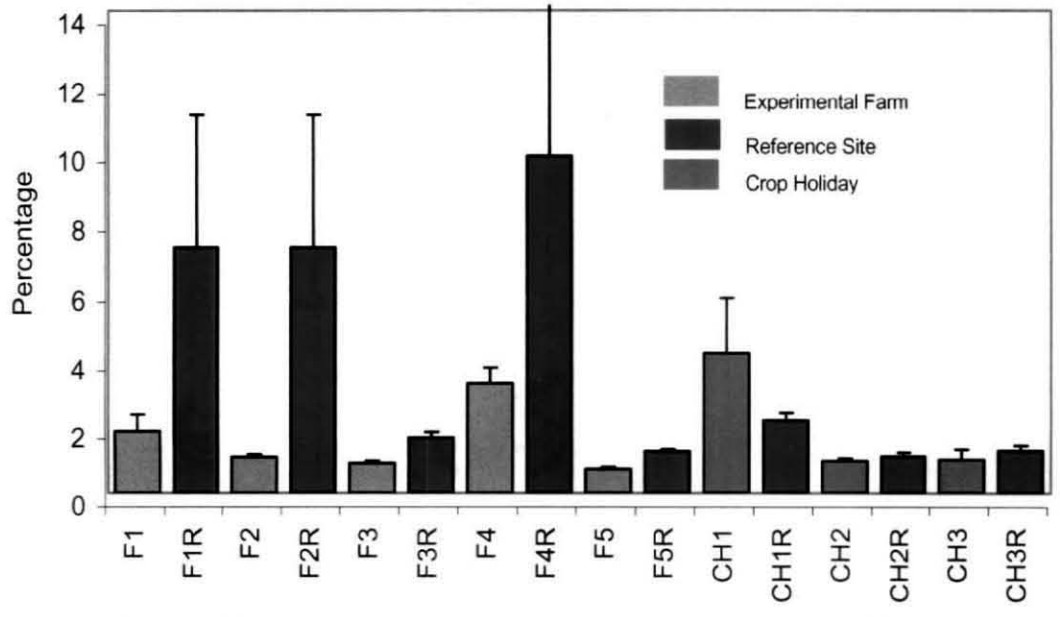

Figure 18b. Change in percentage coarse sand in 5-10 cm of sediment in different oyster farms. Vertical bars indicate standard error

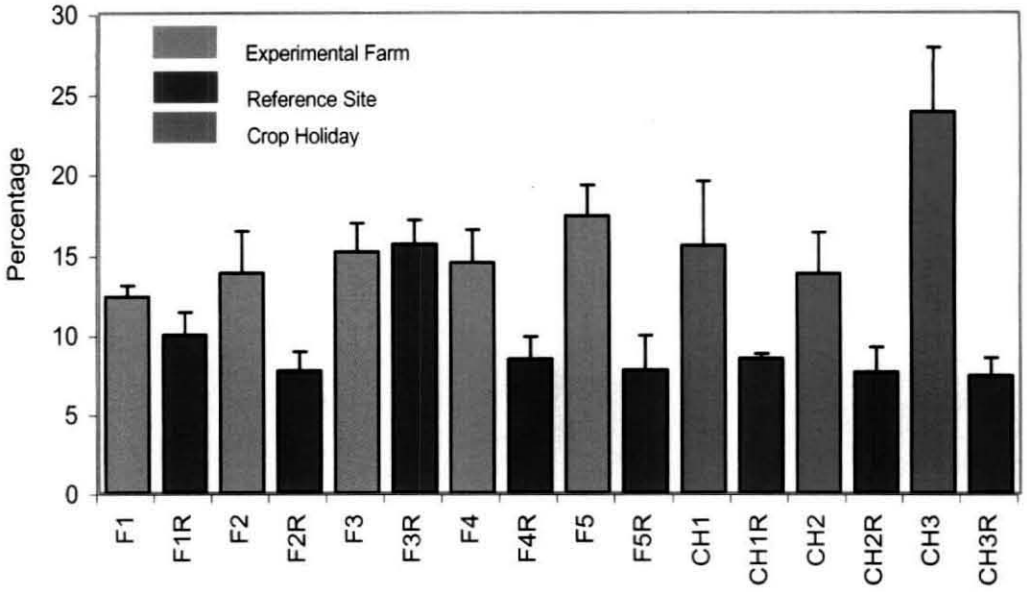

Figure 19a. Change in percentage silt in upper 5 cm of sediment in different oyster farms. Vertical bars indicate standard error

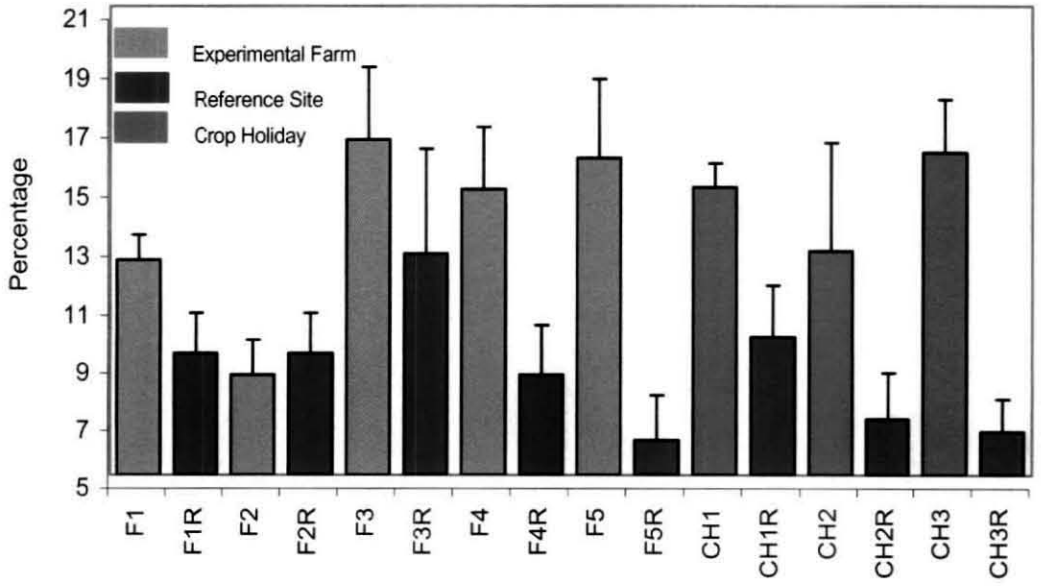

Figure 19b. Change in percentage silt in 5-10 cm of sediment in different oyster farms. Vertical bars indicate standard error

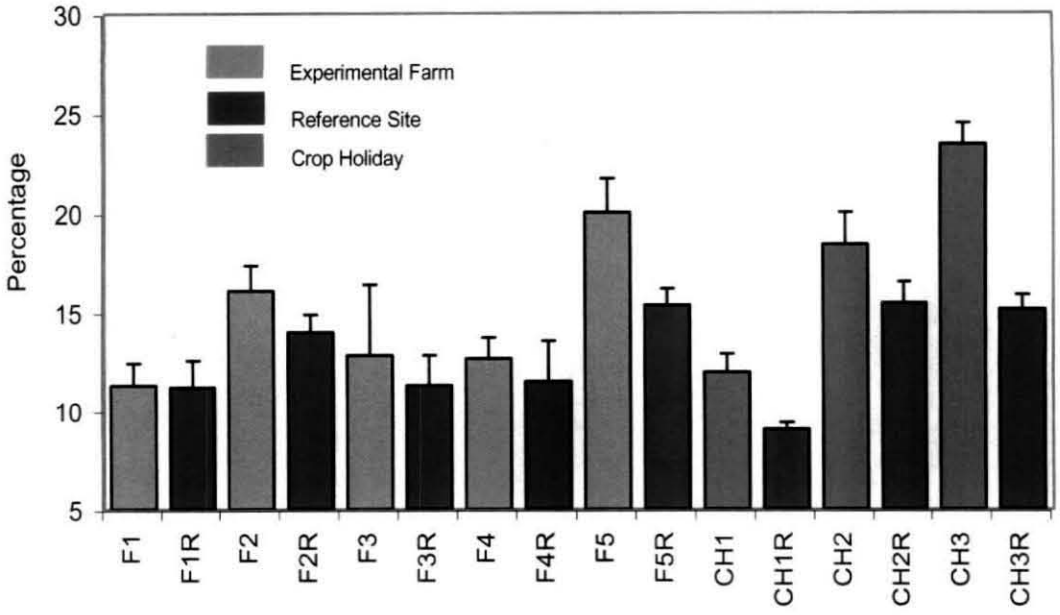

Figure 20a. Change in percentage clay in upper 5 cm of sediment in different oyster farms. Vertical bars indicate standard error

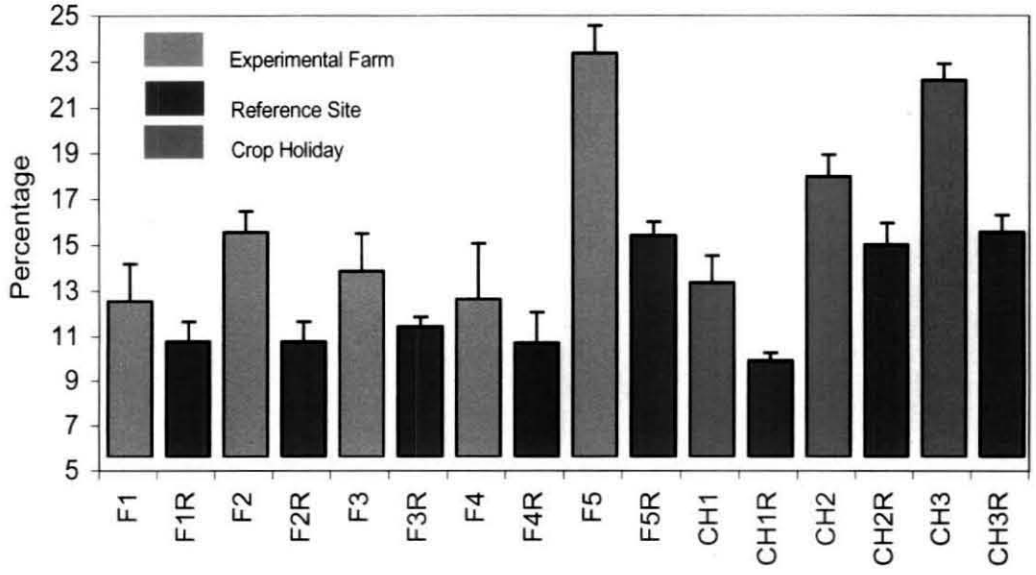

Figure 20b. Change in percentage clay in 5-10 cm of sediment in different oyster farms. Vertical bars indicate standard error

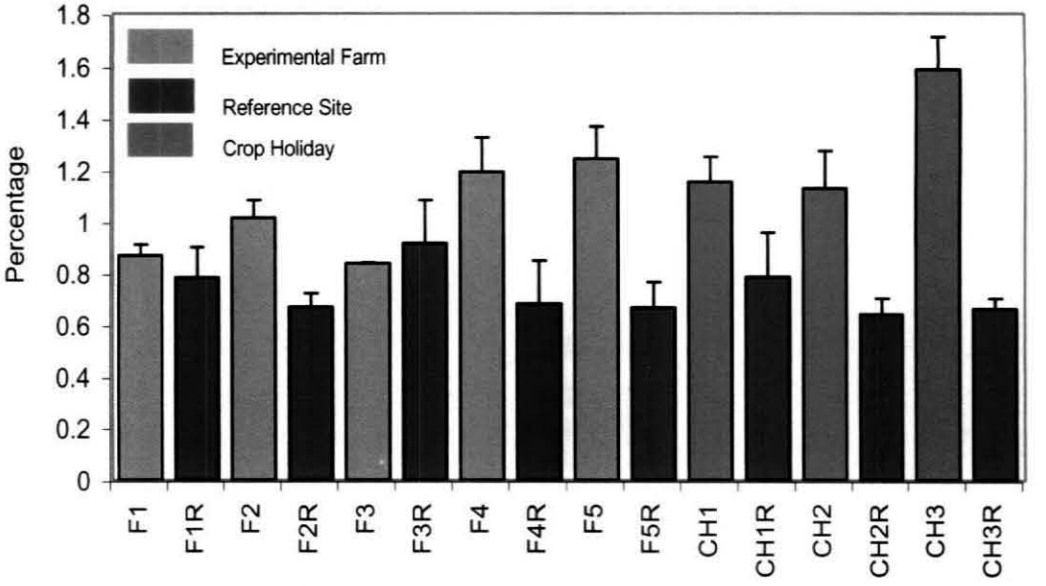

Figure 21a. Change in percentage organic carbon in upper 5 cm of sediment in different oyster farms. Vertical bars indicate standard error

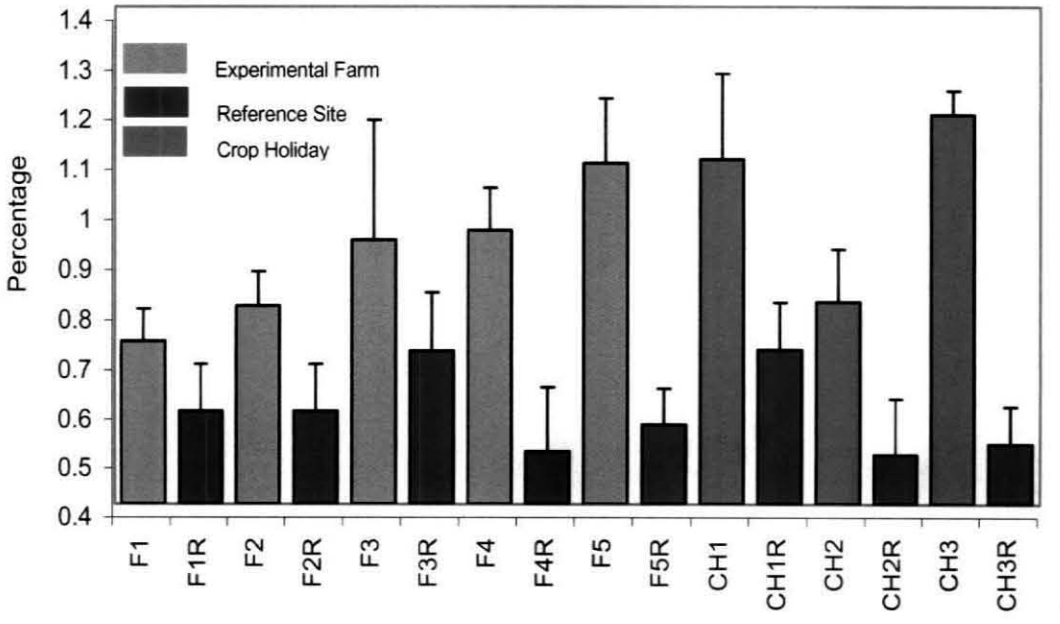

Figure 21b. Change in percentage organic carbon in 5-10 cm of sediment in different oyster farms. Vertical bars indicate standard error

4.4 Impact Assessment on Benthic Macrofauna

4.4.1 Abundance

4.4.1.1 Number of Individuals (N)

The benthic faunal community at the culture and reference sites consisted of different species of Annelids, Crustaceans, Molluscs and Finfishes. The average abundance (no. m^{-2}) at farm and reference sites under different farming and crop holiday periods are shown Table 23 & 24. The numbers of individuals were always higher at the reference site when compared to the farm sites studied. Among the farm and the reference sites under farming periods, the maximum number of individuals occurred at the reference site of F2 (4280 no. m^{-2}) and the minimum, (279 no. m^{-2}) at farm site of F4.

The number of individuals was more or less similar for both the sites during initial farming periods (1278 no. m^{-2} at farm site and 1470 no. m^{-2} at reference site of F1) and it decreased to 1076 no. m^{-2}, which is almost one fourth of the individuals found at reference site of F2 (4280 no. m^{-2}). Gradual reduction in number of individuals in farm sites of F3 (503 no. m^{-2}) and F4 (279 no. m^{-2}) could be observed and a slight improvement at the end of farming period was recorded for F5 (669 no. m^{-2}) (Table 23). The numbers of individuals found at the corresponding reference sites were1757 no. m^{-2} for F3, 978 no. m^{-2} for F4 and 3050 no. m^{-2} for F5. Improvement in number of individuals was observed for CH2 (1265 no. m^{-2} for farm site against 1601 no. m^{-2} at reference site) whereas wide differences were noticeable for CH1 & CH3 sites (Table 24).

Crustaceans were the dominant group in F1 farm site, forming 59.6 % (762 no. m^{-2}) of the benthic community followed by Annelids (36.9 %), Mollusca (1%) (Fig. 22a). At the corresponding reference site, Annelids contributed to 53.2% while crustaceans formed 42.1% and the Mollusca 2.9% of total benthic community (Fig. 22b).

At F2 farm site Annelids formed 73.6% of the total benthic community, followed by crustaceans (23.1%) and the rest was contributed by finfish and unidentified groups (Fig. 23a). In the corresponding reference site, crustaceans

dominated (56.8%), while abundance of Annelids was 40.9%. and the remaining contributed by Molluscs (1.9 %) (Fig. 23b).

At F3 farm site Crustaceans were the dominant group (66.6%) and the Annelids formed 33.4 % (Fig. 24a). In the corresponding reference site, Annelids formed 44.6 % followed by crustaceans 39.6%, Molluscs (11.1%) (Fig. 24b).

At F4 sites the benthic community was not as rich as the other farm sites. The abundance even at the reference site was also low. Annelids were the dominant group, contributing to 86.6 % and 61.9% of the benthos of the farm and reference site respectively. Crustaceans formed 13.4% and 37.1% of the community. Finfish and Mollusca groups were not observed from these sites (Fig. 25a & 25b).

At F5 farm site the abundance was very low (669 no. m^{-2}) compared to that of reference site (3050 no. m^{-2}). Crustaceans with an abundance of 400 no. m^{-2} (59.7%) formed the dominant component at the farm site followed by annelids (38.9%) (Fig. 26a). In the corresponding reference site, Annelids formed 64.4% of the community with an abundance of 1963 no. m^{-2} followed by crustaceans (34.7%). Molluscs were absent at the farm site but formed 0.6% (19 no. m^{-2}) at the reference site (Fig. 26b). Fin fishes formed 1.4% of the community at F5 farm site while at the references site these were absent.

The benthic communities at the farm sites under crop holiday periods CH1 (1377 no. m^{-2}) and CH2 (1265 no. m^{-2}) were richer than the farm sites under farming periods (F3, F4 & F5) indicating improvement during crop holiday period even though the abundance was lower than the corresponding reference sites. Annelids formed 81.07% of the community at CH1 farm site, followed by crustaceans, 16.22% (Fig. 27a). In the corresponding reference site, the benthic community was composed of crustaceans (31.73%), Annelids (63.57%), and Mollusca (3.36%) (Fig. 27b). Finfish group formed 1.36% of the community at farm site but were absent from the reference site.

At the CH2 farm site, the abundance was almost similar to that of the reference site and annelids dominated the community with 52.99%, followed by Crustacea with 46.27% (Fig. 28a). However the species composition for the

corresponding reference site was slightly different. Here the Annelids dominated the community with 76.19%, followed by Crustacea (20.31%) and Mollusca (3.5%) (Fig. 28b).

Though CH3 was of a longer duration crop holiday period, the abundance of benthic communities (509 no. m^{-2}) was lower when compared to that of the F5 farm site (669 no. m^{-2}) and was much lower than the corresponding reference site (2852 no. m^{-2}). At both the sites crustacea was the dominant group (54.86% for farm site and 53.86% for reference site) followed by Annelida (42.70% for farm site and 44.39% for reference site) (Fig. 29a & 29b).

4.4.1.2 Total Number of Species (S)

The maximum numbers of species (33) were recorded from the F2 reference site and the minimum (6) from F3 farm site (Table 25). In general, it was observed that Annelids were the dominant group in terms of the number of species contributing to the benthic community and their number decreased with continuous farming and remained more or less constant for the crop holiday sites.

The number of species in the initial farming period was more at the farm site (30) and the numbers declined to 6 at the end of third year of farming. At F4 and F5, the number of species contributing to the faunal structure was found to be 10 and 12 while the corresponding reference sites had 21 and 28 no. of species.

The number of species was comparatively higher at the farm sites under crop holiday periods than farm sites under farming periods (Table 25). While at the corresponding reference sites the total number of species was 21, 24 and 26 respectively.

4.4.2 Diversity

4.4.2.1 Univariate Diversity Indices

Univariate diversity measures of farm and reference sites of different farming and crop holiday periods are given in Table 25. Even though the abundance of benthic macrofaunal communities was less at the sites under F3 and F5 farming

periods, the species were more evenly distributed at these sites as indicated by Piolou's (J') evenness index. Maximum Shannon diversity index and Margalef species richness index values were recorded from farm and reference sites of F1; and the minimum values from F3 sites. Differences in the values of Pielou's (J') evenness index, Shannon H' diversity index and Simpson (1-λ) dominance index observed between different farm and reference sites, were not significant ($p>0.05$). When compared to F3, F4 and F5 sites. The different diversity indices increased during the crop holiday periods indicating a positive impact.

4.4.3 Multivariate analysis

4.4.3.1 ANOSIM

The average species similarity percentages recorded from the sites of different farming and crop holiday periods are given in Table 26. Maximum species similarity was observed for F3 site and minimum similarity in F5 farm site and F4 reference site. The species similarity percentage was almost same for both farm and reference sites of CH2 (Table 26). Comparatively low similarity percentages in all sites except F3 indicated that there were more seasonal variations within the site.

Analysis of similarity between farm and reference sites of various farming and crop holiday periods was accomplished by calculating global the R statistic values and the values are presented in Table 27. Among the different farming periods highest dissimilarity percentage was observed between farm and reference sites of F5 and the lowest in F3 sites. Highest dissimilarity of 91.54 % was observed between farm and reference sites of CH3.

Multivaraite analysis of the abundance of the benthic macrofauna showed absolute difference between the farm and reference sites of third year farming period (ANOSIM: $R = 1.00$, $p<0.001$). Significant differences in abundance of benthic macrofauna were also observed between farm and reference sites of F4 (ANOSIM: $R = 0.40$, $p<0.001$), F5 (ANOSIM: $R = 0.36$ $p<0.001$) and CH3 (ANOSIM: $R = 0.41$, $p<0.001$) (Table 27) with more individuals in the reference site than the farm sites.

4.4.3.2 SIMPER

SIMPER analysis on the contribution of each taxa could be observed for the dissimilarity found among the sites of different farming and crop holiday periods (Tables 28 to 35). *Gammarus* sp contributed 22.84%, 30.61%, 15.19%, 39.44%, 18.23% and 24.85% to average dissimilarity observed between farm and reference sites of F1, F2, F4, CH1, CH2 and CH3 respectively. *Apseudus chilkensis* contributed 21.28% and *Notomastus aberans* contributed 24.17% of dissimilarity between farm and reference sites of F3 and F5 respectively. *Notomastus fauveli*, *N. latericeus*, *Megalomma quadrioculatum* and *Glycera unicornis* which contributed < 5% to the average dissimilarity were consistently present all the sites indicating that these species are ubiquitously distributed.

Table 23 Average abundance (no. m^{-2}) of benthic macrofauna at farm and reference sites of different farming periods

	F1		F2		F3		F4		F5	
Species	**Farm**	**Reference**	**Farm**	**Reference**	**Farm**	**Reference**	**Farm**	**Reference**	**Farm**	**Reference**
Ancistrosyllis constricta	0	0	0	30	0	0	0	0	0	56
Ancistrosyllis parva	6	12	0	25	0	0	0	19	0	28
Ancistrosyllis robusta	19	6	10	0	0	0	0	9	0	0
Boccardia polybranchia	0	0	10	0	0	0	9	0	0	0
Branchiomaldane vincenti	0	0	5	61	0	0	0	0	28	37
Capitella capitata	81	118	289	188	0	0	28	65	83	195
Ceratonereis keiskama	19	44	25	15	0	28	0	28	9	19
Ceratonereis mirabilis	25	0	0	0	0	0	0	0	0	0
Cirriformia filigera	0	0	0	30	0	0	0	0	0	56
Cossura coasta	31	31	56	0	0	84	9	19	0	0
Diopatra monroi	0	62	0	15	0	0	0	93	0	28
Diopatra neapolitana capensis	25	0	0	51	0	0	0	0	0	84
Drilonereis longa	19	37	0	0	0	168	0	0	0	0
Drilonereis monroi	0	0	0	20	0	0	0	0	0	19
Glycera unicornis	0	12	10	101	0	0	0	9	0	37
Glycinde kameruniana	0	44	0	36	0	0	0	65	0	37
Lumbrineris heteropoda	0	6	0	20	0	0	9	0	0	28
Lumbrineris magalhaensis	12	0	0	10	0	0	0	0	0	19
Lysilla loveni	19	19	0	0	0	84	0	0	0	0
Maldanella harai	31	19	0	0	0	0	37	28	0	0
Mediomastus capensis	0	19	15	15	0	0	0	0	0	28
Megalomma quadrioculatum	0	6	31	138	0	0	0	9	0	93
Nephtys dibranchis	0	0	5	15	0	0	0	0	0	28
Nephtys macroura	12	0	25	46	0	0	0	0	46	47
Nephtys polybranchia	68	68	0	0	56	195	9	37	0	0
Nerindes gilchristi	6	19	0	0	0	0	0	0	0	0
Notomastus aberans	6	105	20	634	0	28	0	102	9	753
Notomastus fauveli	6	37	15	86	0	0	0	9	0	121
Notomastus latericeus	6	25	36	107	0	0	0	37	0	158
Petaloproctus terricola	12	31	0	0	28	0	0	46	0	0
Polydora capensis	0	0	10	41	0	0	0	0	0	74
Prinospio cirrifera	12	37	188	15	84	168	56	0	19	9
Prinospio cirrobranchiata	25	0	0	25	0	0	84	0	9	0
Prinospio pinnata	12	12	0	0	0	0	0	19	0	0
Pulliella armata	0	0	5	15	0	0	0	0	0	9
Sabella penicillus	0	0	20	0	0	0	0	0	0	0
Serpula vermicularis	0	0	0	0	0	0	0	0	56	0
Spio filicornis	0	0	15	5	0	0	0	0	0	0
Spiophanes bombyx	19	12	0	0	0	28	0	9	0	0
Syllidia armata	0	0	0	5	0	0	0	0	0	0
ANNELIDA TOTAL	**472**	**782**	**791**	**1751**	**168**	**783**	**242**	**606**	**260**	**1963**
Alpheus sp	6	0	0	10	0	0	0	0	9	0
Ampithoe sp	31	0	0	0	0	0	0	0	0	0
Apseudus chilkensis	167	161	122	279	251	556	0	56	344	130
Penaeus sp	19	6	20	0	28	0	19	9	0	0
Gammarus sp	452	452	106	2143	0	139	19	298	47	929
Tanaidacea sp	86	0	0	0	56	0	0	0	0	0
CRUSTACEA TOTAL	**762**	**619**	**249**	**2432**	**335**	**695**	**37**	**363**	**400**	**1059**
Arca sp	0	0	0	10	0	0	0	0	0	9
Macoma sp	0	0	0	5	0	0	0	0	0	0
Paphia malabarica	12	43	0	56	0	195	0	0	0	9
MOLLUSCA TOTAL	**12**	**43**	**0**	**71**	**0**	**195**	**0**	**0**	**0**	**19**
Gobioides sp	0	0	10	0	0	0	0	0	9	0
FINFISH TOTAL	**0**	**0**	**10**	**0**	**0**	**0**	**0**	**0**	**9**	**0**
Unidentified	31	25	25	25	0	84	0	9	0	9
GRAND TOTAL	**1278**	**1470**	**1076**	**4280**	**503**	**1757**	**279**	**978**	**669**	**3050**

Table 24 Average abundance (no. m^{-2}) of benthic macrofauna at crop holiday and reference sites of different crop holiday periods

	CH1		CH2		CH3	
Species	**Farm**	**Reference**	**Farm**	**Reference**	**Farm**	**Reference**
Ancistrosyllis constricta	0	0	0	0	0	0
Ancistrosyllis parva	19	37	0	28	0	19
Ancistrosyllis robusta	19	0	0	9	0	6
Boccardia polybranchia	19	0	0	19	0	12
Branchiomaldane vincenti	0	0	65	177	0	168
Capitella capitata	204	390	0	158	12	149
Ceratonereis keiskama	0	75	37	0	12	0
Ceratonereis mirabilis	0	0	0	0	0	0
Cirriformia filigera	19	0	0	9	0	6
Cossura coasta	19	0	19	37	12	25
Diopatra monroi	0	0	0	0	0	0
Diopatra neapolitana capensis	0	0	19	140	0	99
Drilonereis longa	0	0	0	0	0	0
Drilonereis monroi	0	37	0	0	0	0
Glycera unicornis	0	186	9	75	0	93
Glycinde kameruniana	0	37	0	19	0	19
Lumbrineris heteropoda	0	19	0	0	0	6
Lumbrineris magalhaensis	0	0	0	0	0	0
Lysilla loveni	0	0	0	0	0	0
Maldanella harai	0	0	0	0	0	0
Mediomastus capensis	0	56	0	9	0	6
Megalomma quadrioculatum	19	244	19	84	0	81
Nephtys dibranchis	0	0	9	19	6	12
Nephtys macroura	19	19	0	28	6	37
Nephtys polybranchia	0	0	0	0	0	0
Nerindes gilchristi	0	56	0	0	0	0
Notomastus aberans	56	223	37	279	12	415
Notomastus fauveli	0	167	0	9	19	6
Notomastus latericeus	0	56	47	84	6	62
Petaloproctus terricola	0	0	0	0	0	0
Polydora capensis	37	0	9	0	0	0
Prinospio cirrifera	242	0	307	28	99	31
Prinospio cirrobranchiata	242	93	0	0	0	0
Prinospio pinnata	0	0	0	0	0	0
Pulliella armata	0	37	0	0	0	0
Sabella penicillus	0	0	0	0	0	0
Serpula vermicularis	0	0	0	0	0	0
Spio filicornis	19	0	74	9	19	12
Spiophanes bombyx	0	0	19	0	12	0
Syllidia armata	186	19	0	0	0	0
ANNELIDA TOTAL	**1116**	**1752**	**670**	**1220**	**217**	**1266**
Alpheus sp	0	0	0	0	19	12
Ampithoe sp	0	0	0	0	0	0
Apseudus chilkensis	186	241	140	112	68	248
Gammarus sp	37	3269	446	214	130	1276
Penaeus sp	0	0	0	0	62	0
Tanaidacea sp	0	0	0	0	0	0
CRUSTACEA TOTAL	**223**	**3511**	**585**	**325**	**279**	**1536**
Arca sp	0	0	0	9	0	12
Macoma sp	0	0	9	19	0	19
Paphia malabarica	0	186	0	28	0	19
MOLLUSCA TOTAL	**0**	**186**	**9**	**56**	**0**	**50**
Gobioides sp	19	0	0	0	6	0
FINFISH TOTAL	**19**	**0**	**0**	**0**	**6**	**0**
Unidentified	19	74	0	0	6	0
GRAND TOTAL	**1377**	**5522**	**1265**	**1601**	**509**	**2852**

Table 25 Diversity measures of farm and reference sites of different farming and crop holiday periods

		Farming period					Crop holiday period		
Diversity measure	Site	F1	F2	F3	F4	F5	CH1	CH2	CH3
Total species (S)	Farm	30	24	6	10	12	18	16	17
	Reference	28	33	12	21	28	21	24	26
Total individuals (N)	Farm	1278	1076	503	279	669	1377	1265	509
	Reference	1470	4280	1757	978	3050	5522	1601	2852
Margalef (d) species richness index	Farm	4.05	3.29	0.80	1.60	1.69	2.35	2.10	2.57
	Reference	3.70	3.83	1.47	2.90	3.37	2.32	3.12	3.14
Pielou's (J') evenness index	Farm	0.75	0.78	0.81	0.87	0.69	0.81	0.72	0.80
	Reference	0.79	0.58	0.86	0.82	0.71	0.58	0.84	0.63
Shannon (H') diversity index	Farm	2.53	2.47	1.46	2.00	1.71	2.34	2.00	2.28
	Reference	2.64	2.02	2.14	2.48	2.36	1.75	2.65	2.05
Simpson (1-λ) dominance index	Farm	0.84	0.87	0.69	0.83	0.70	0.88	0.80	0.86
	Reference	0.87	0.72	0.84	0.87	0.83	0.63	0.91	0.76

Table 26 Average similarity percentages for within the sites of different farming and crop holiday periods

Farming / crop holiday period	Site	Average Similarity percentage
One year farming (F1)	Farm	14.28
	Reference	16.28
Two year farming (F2)	Farm	12.60
	Reference	27.93
Three year farming (F3)	Farm	44.53
	Reference	69.83
Four year farming (F4)	Farm	16.28
	Reference	15.45
Five year farming (F5)	Farm	8.14
	Reference	31.93
Three months crop holiday(CH1)	Farm	16.86
	Reference	22.66
Six months crop holiday (CH2)	Farm	21.16
	Reference	21.01
Nine months crop holiday(CH3)	Farm	15.38
	Reference	18.15

Table 27 Average dissimilarity percentage and global R statistic values for different farming and crop holiday periods

Groups	Average dissimilarity percentage	Global R Statistic value
Farm vs Reference site of F1	82.76	-0.07
Farm vs Reference site of F2	89.22	0.27
Farm vs Reference site of F3	65.93	1.00
Farm vs Reference site of F4	93.56	0.40
Farm vs Reference site of F5	88.95	0.36
Farm vs Reference site of CH1	86.26	0.11
Farm vs Reference site of CH2	84.80	0.24
Farm vs Reference site of CH3	91.54	0.41

Table 28 SIMPER analysis results showing the taxa that contributed with more than 90% of the dissimilarity between farm and reference sites of F1

Species	Average dissimilarity ± SD	Contribution %	Cumulative %
Gammarus sp	18.91 ± 0.99	22.84	22.84
Apseudus chilkensis	8.36 ± 1.04	10.10	32.95
Capitella capitata	5.71 ± 1.05	6.89	39.84
Nephtys polybranchia	5.34 ± 0.70	6.46	46.30
Notomastus aberans	4.28 ± 0.69	5.18	51.47
Diopatra monroi	3.48 ± 0.61	4.21	55.68
Cossura coasta	2.80 ± 0.67	3.38	59.07
Maldanella harai	2.53 ± 0.45	3.06	62.12
Petaloproctus terricola	2.08 ± 0.36	2.52	64.64
Glycinde kameruniana	2.02 ± 0.44	2.44	67.08
Prinospio cirrifera	1.98 ± 0.70	2.40	69.47
Ceratonereis keiskama	1.97 ± 0.73	2.38	71.85
Tanaidacea sp	1.84 ± 0.46	2.22	74.07
Paphia malabarica	1.81 ± 0.44	2.19	76.26
Unidentified	1.76 ± 0.72	2.12	78.38
Drilonereis longa	1.63 ± 0.60	1.98	80.36
Notomastus fauveli	1.50 ± 0.56	1.81	82.17
Prinospio pinnata	1.39 ± 0.38	1.68	83.85
Prinospio cirrobranchiata	1.37 ± 0.45	1.66	85.51
Notomastus latericeus	1.31 ± 0.54	1.58	87.09
Ancistrosyllis robusta	1.25 ± 0.58	1.51	88.60
Penaeus sp	1.22 ± 0.46	1.48	90.07

Table 29SIMPER analysis results showing the taxa that contributed with more than 90% of the dissimilarity between farm and reference sites of F2

Species	Average dissimilarity ± SD	Contribution %	Cumulative %
Gammarus sp	27.31 ± 0.97	30.61	30.61
Notomastus aberans	14.17 ± 1.28	15.88	46.49
Apseudus chilkensis	10.06 ± 0.67	11.27	57.76
Capitella capitata	6.96 ± 0.85	7.80	65.56
Prinospio cirrifera	3.52 ± 0.56	3.95	69.51
Megalomma quadrioculatum	2.51 ± 0.98	2.81	72.32
Notomastus latericeus	2.42 ± 0.92	2.71	75.03
Glycera unicornis	2.29 ± 0.97	2.56	77.59
Notomastus fauveli	2.14 ± 0.58	2.40	79.99
Branchiomaldane vincenti	1.97 ± 0.54	2.21	82.19
Nephtys macroura	1.62 ± 0.49	1.82	84.01
Polydora capensis	1.11 ± 0.47	1.25	85.26
Glycinde kameruniana	1.00 ± 0.88	1.12	86.37
Cossura coasta	0.98 ± 0.49	1.10	87.47
Diopatra neapolitana capensis	0.93 ± 0.60	1.04	88.51
Ancistrosyllis parva	0.87 ± 0.48	0.98	89.49
Unidentified	0.87 ± 0.41	0.97	90.46

Table 30 SIMPER analysis results showing the taxa that contributed with more than 90% of the dissimilarity between farm and reference sites of F3

Species	Average dissimiarity ± SD	Contribution %	Cumulative %
Apseudus chilkensis	14.03 ± 1.69	21.28	21.28
Paphia malabarica	8.76 ± 1.19	13.28	34.56
Drilonereis longa	7.48 ± 11.54	11.34	45.90
Gammarus sp	6.23 ± 1.42	9.45	55.35
Nephtys polybranchia	6.17 ± 4.41	9.36	64.71
Lysilla loveni	3.75 ± 2.45	5.69	70.40
Cossura coasta	3.69 ± 0.86	5.60	76.00
Unidentified	3.69 ± 0.86	5.60	81.60
Prinospio cirrifera	3.65 ± 3.25	5.53	87.12
Tanaidacea sp	2.31 ± 0.87	3.50	90.62

Table 31 SIMPER analysis results showing the taxa that contributed with more than 90% of the dissimilarity between farm and reference sites of F4

Species	Average dissimilarity ± SD	Contribution %	Cumulative %
Gammarus sp	14.21 ± 0.73	15.19	15.19
Prinospio cirrobranchiata	8.99 ± 0.75	9.61	24.80
Diopatra monroi	7.93 ± 0.89	8.48	33.28
Notomastus aberans	7.34 ± 0.75	7.85	41.13
Apseudus chilkensis	6.45 ± 0.89	6.90	48.02
Capitella capitata	6.35 ± 0.92	6.79	54.81
Prinospio cirrifera	6.07 ± 0.72	6.49	61.30
Maldanella harai	5.40 ± 0.56	5.77	67.07
Glycinde kameruniana	4.29 ± 0.64	4.59	71.66
Petaloproctus terricola	4.18 ± 0.44	4.46	76.12
Nephtys polybranchia	4.02 ± 0.71	4.30	80.42
Penaeus sp	2.59 ± 0.58	2.77	83.19
Notomastus latericeus	2.56 ± 0.68	2.74	85.93
Cossura coasta	2.34 ± 0.72	2.50	88.43
Notomastus fauveli	1.72 ± 0.43	1.84	90.27

Table 32 SIMPER analysis results showing the taxa that contributed with more than 90% of the dissimilarity between farm and reference sites of F5

Species	Average dissimilarity ± SD	Contribution %	Cumulative %
Notomastus aberans	21.50 ± 2.19	24.17	24.17
Gammarus sp	15.62 ± 0.88	17.57	41.74
Apseudus chilkensis	14.75 ± 1.15	16.58	58.32
Capitella capitata	5.14 ± 1.39	5.77	64.09
Notomastus latericeus	4.12 ± 1.64	4.63	68.73
Notomastus fauveli	3.22 ± 0.64	3.62	72.34
Nephtys macroura	3.06 ± 0.48	3.44	75.79
Branchiomaldane vincenti	2.90 ± 0.54	3.26	79.04
Megalomma quadrioculatum	2.33 ± 0.84	2.62	81.66
Glycera unicornis	1.88 ± 0.67	2.11	83.77
Diopatra neapolitana capensis	1.70 ± 0.89	1.91	85.68
Ancistrosyllis parva	1.66 ± 0.62	1.86	87.54
Polydora capensis	1.63 ± 0.53	1.84	89.38
Cirriformia filigera	1.18 ± 0.44	1.33	90.71

Table 33 SIMPER analysis results showing the taxa that contributed with more than 90% of the dissimilarity between farm and reference sites of CH1

Species	Average dissimilarity ± SD	Contribution %	Cumulative %
Gammarus sp	34.02 ± 1.24	39.44	39.44
Notomastus aberans	6.32 ± 0.86	7.33	46.77
Apseudus chilkensis	6.29 ± 0.83	7.29	54.06
Capitella capitata	5.87 ± 1.40	6.81	60.87
Prinospio cirrobranchiata	4.89 ± 1.02	5.67	66.54
Prinospio cirrifera	3.46 ± 0.59	4.01	70.54
Notomastus fauveli	3.22 ± 1.49	3.73	74.28
Glycera unicornis	3.20 ± 1.41	3.71	77.98
Megalomma quadrioculatum	3.16 ± 1.26	3.67	81.65
Syllidia armata	2.72 ± 0.61	3.16	84.80
Paphia malabarica	1.46 ± 0.66	1.69	86.50
Ceratonereis keiskama	1.28 ± 0.77	1.49	87.98
Mediomastus capensis	1.14 ± 0.64	1.32	89.30
Nerindes gilchristi	1.14 ± 0.64	1.32	90.62

Table 34 SIMPER analysis results showing the taxa that contributed with more than 90% of the dissimilarity between farm and reference sites of CH2

Species	Average dissimilarity ± SD	Contribution %	Accumulated %
Gammarus sp	15.46 ± 0.71	18.23	18.23
Prinospio cirrifera	12.12 ± 0.87	14.29	32.52
Notomastus aberans	10.67 ± 1.00	12.58	45.11
Apseudus chilkensis	8.72 ± 0.66	10.28	55.39
Branchiomaldane vincenti	5.83 ± 1.22	6.87	62.26
Diopatra neapolitana capensis	3.99 ± 0.96	4.70	66.96
Capitella capitata	3.89 ± 0.77	4.59	71.55
Cossura coasta	3.53 ± 0.42	4.16	75.71
Megalomma quadrioculatum	3.10 ± 0.78	3.65	79.36
Spio filicornis	2.93 ± 0.86	3.46	82.82
Notomastus latericeus	2.89 ± 0.90	3.41	86.23
Glycera unicornis	2.44 ± 0.99	2.88	89.11
Nephtys macroura	1.84 ± 0.73	2.17	91.28

Table 35 SIMPER analysis results showing the taxa that contributed with more than 90% of the dissimilarity between farm and reference sites of CH3

Species	Average dissimilarity ± SD	Contribution %	Accumulated %
Gammarus sp	22.75 ± 0.79	24.85	24.85
Apseudus chilkensis	13.36 ± 0.69	14.60	39.45
Notomastus aberans	11.78 ± 0.94	12.86	52.31
Prinospio cirrifera	5.11 ± 0.61	5.59	57.90
Branchiomaldane vincenti	4.64 ± 0.78	5.07	62.97
Capitella capitata	4.02 ± 0.87	4.39	67.36
Diopatra neapolitana capensis	3.56 ± 0.80	3.89	71.26
Cossura coasta	3.46 ± 0.38	3.79	75.04
Glycera unicornis	3.04 ± 1.26	3.32	78.36
Notomastus latericeus	2.81 ± 0.83	3.07	81.43
Penaeus sp	2.71 ± 0.44	2.96	84.39
Megalomma quadrioculatum	2.50 ± 0.56	2.74	87.13
Nephtys macroura	1.88 ± 0.69	2.05	89.18
Spio filicornis	1.23 ± 0.44	1.34	90.52

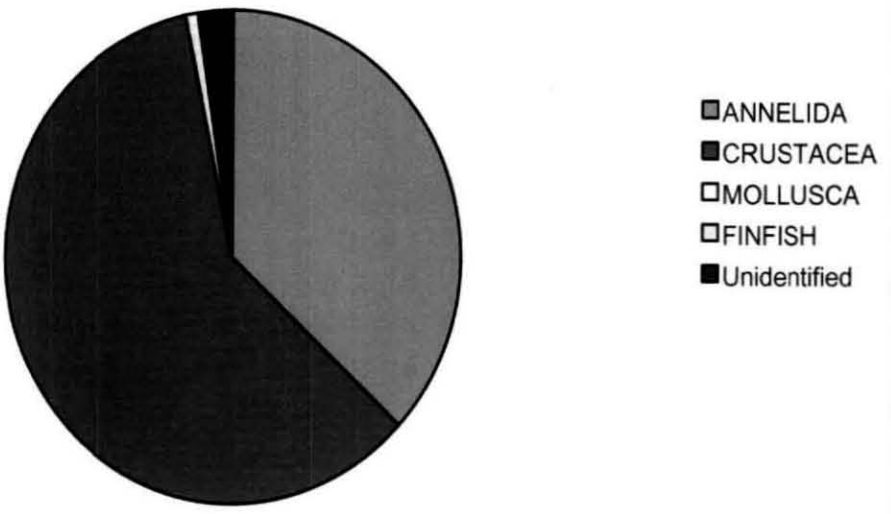

Figure 22a. Percentage abundance of different benthic macrofaunal groups at farm site in first year

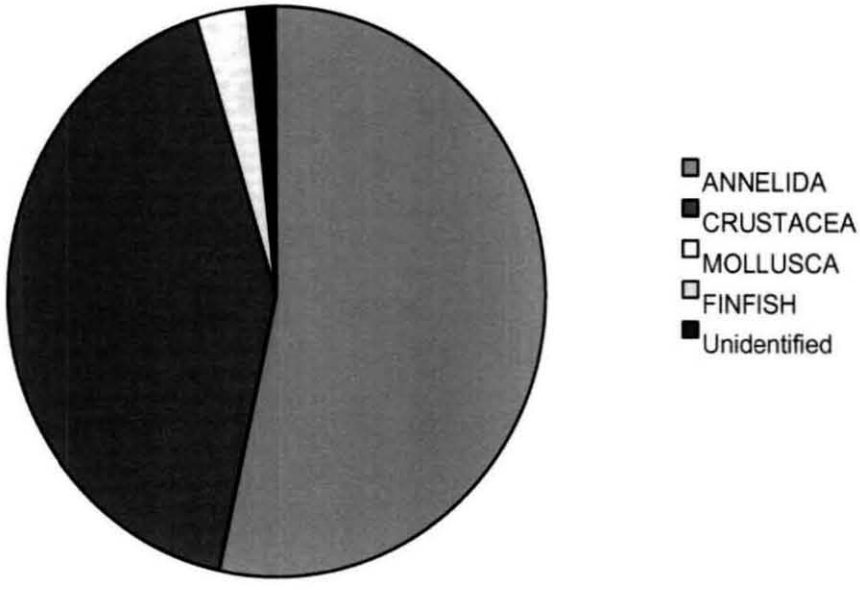

Figure 22b. Percentage abundance of different benthic macrofaunal groups at reference site in first year

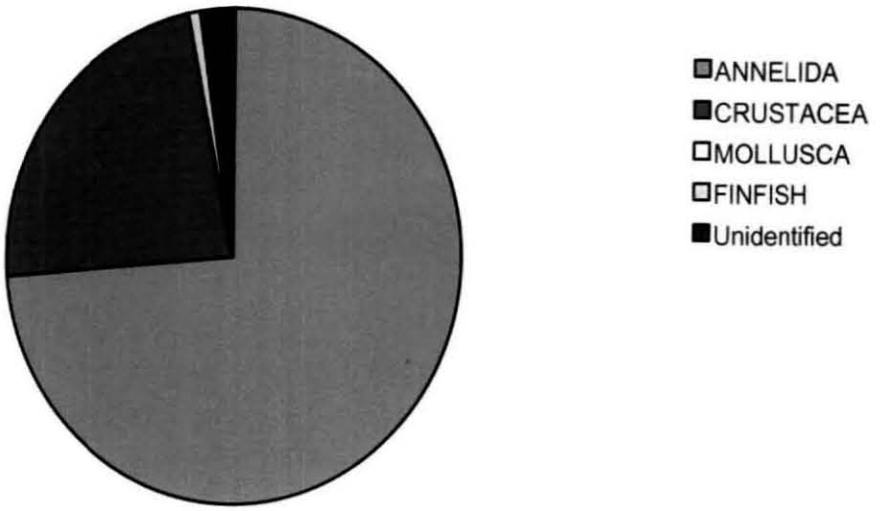

Figure 23a. Percentage abundance of different benthic macrofaunal groups at farm site in second year

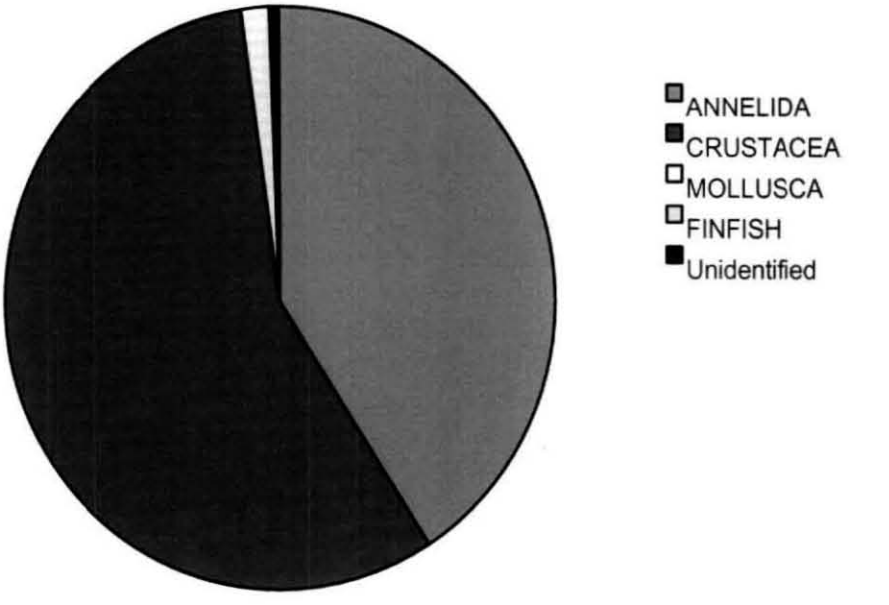

Figure 23b. Percentage abundance of different benthic macrofaunal groups at reference site in second year

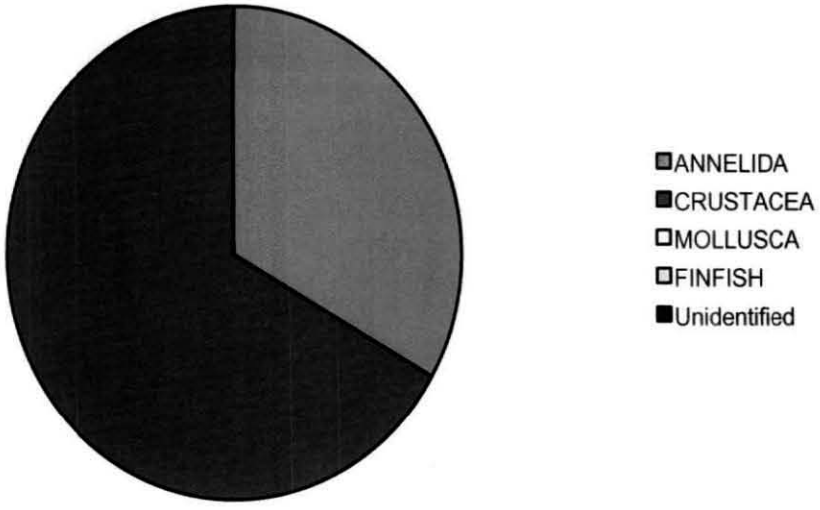

Figure 24a. Percentage abundance of different benthic macrofaunal groups at farm site in third year

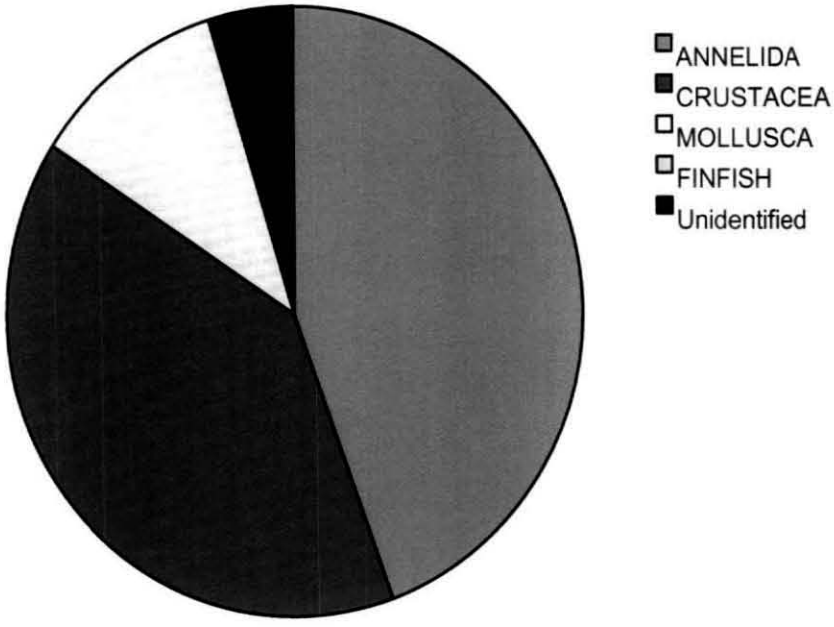

Figure 24b. Percentage abundance of different benthic macrofaunal groups at reference site in third year

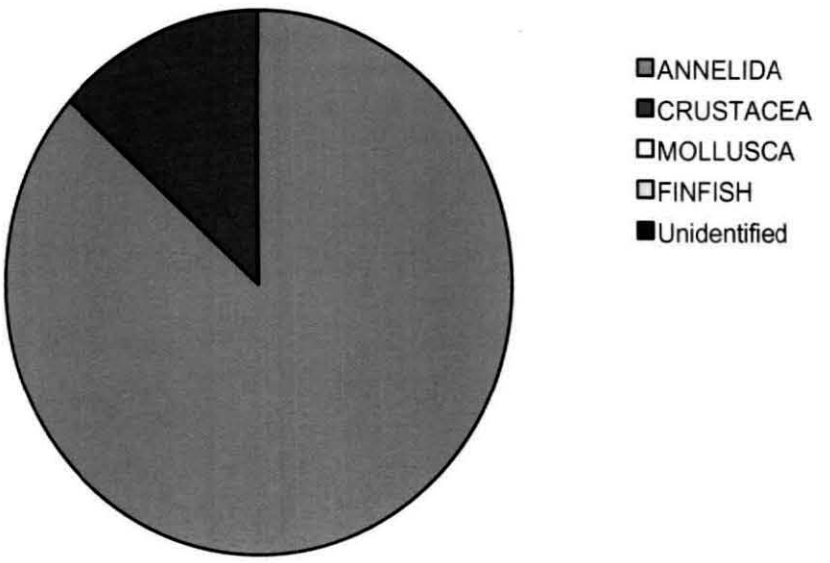

Figure 25a. Percentage abundance of different benthic macrofaunal groups at farm site in fourth year

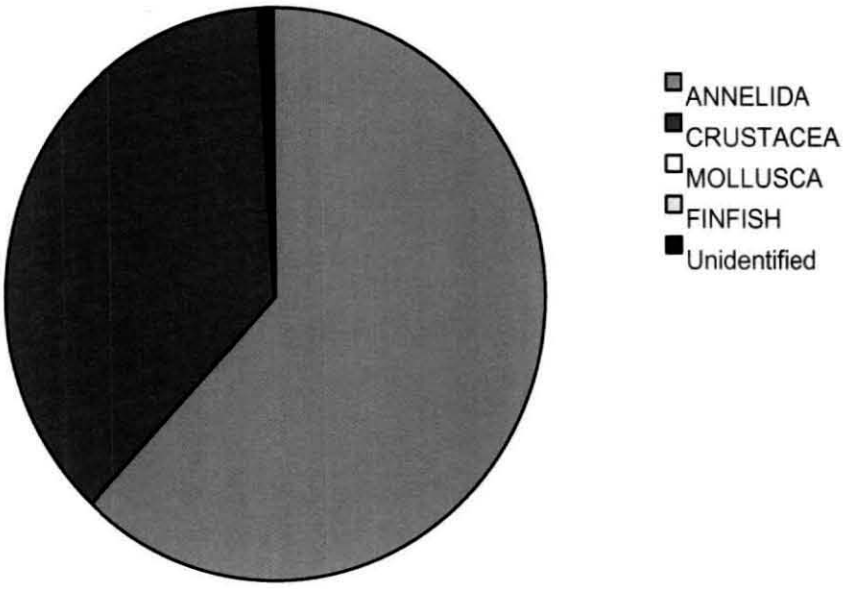

Figure 25b. Percentage abundance of different benthic macrofaunal groups at reference site in fourth year

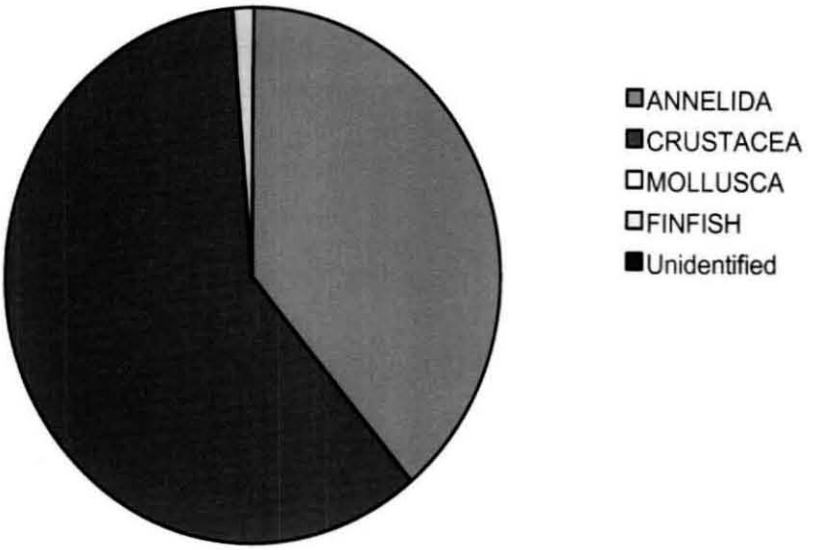

Figure 26a. Percentage abundance of different benthic macrofaunal groups at farm site in fifth year

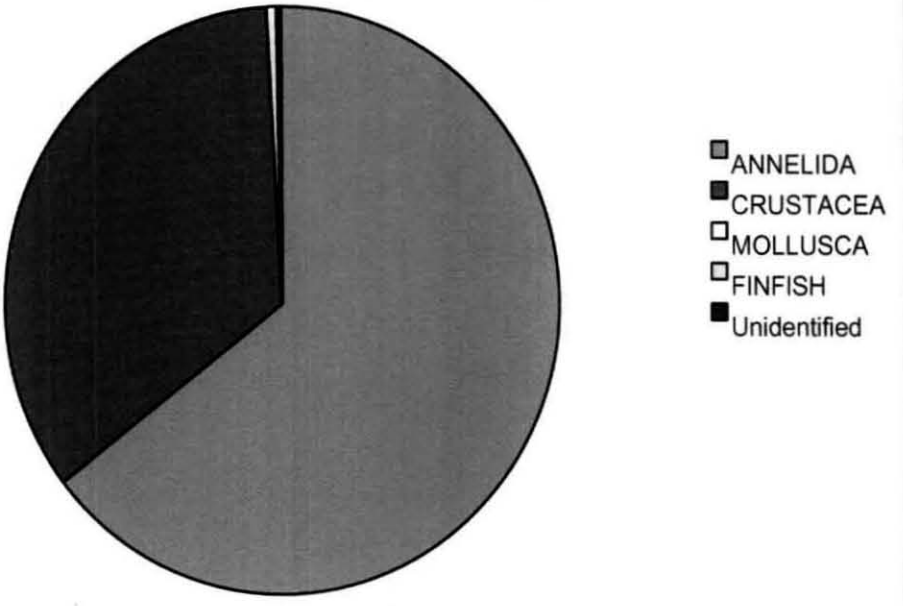

Figure 26b. Percentage abundance of different benthic macrofaunal groups at reference site in fifth year

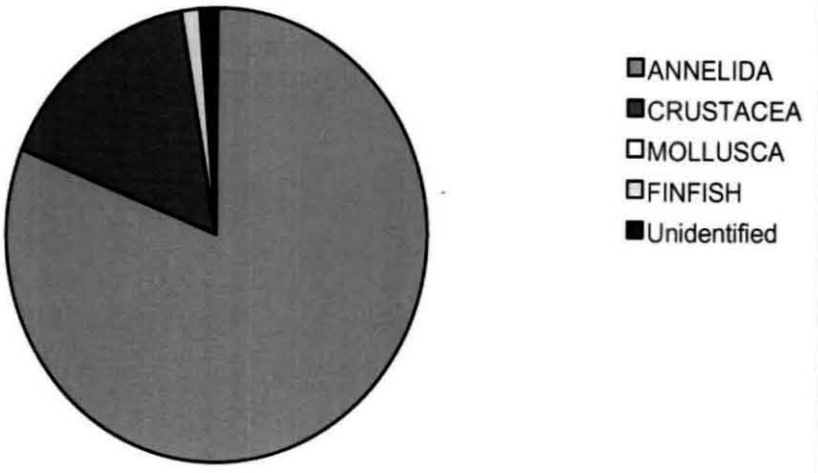

Figure 27a. Percentage abundance of different benthic macrofaunal groups at farm site of CH1

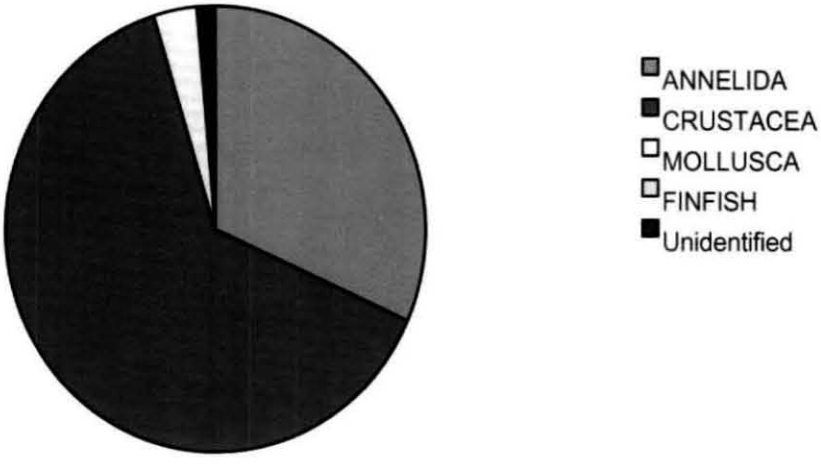

Figure 27b. Percentage abundance of different benthic macrofaunal groups at reference site of CH1

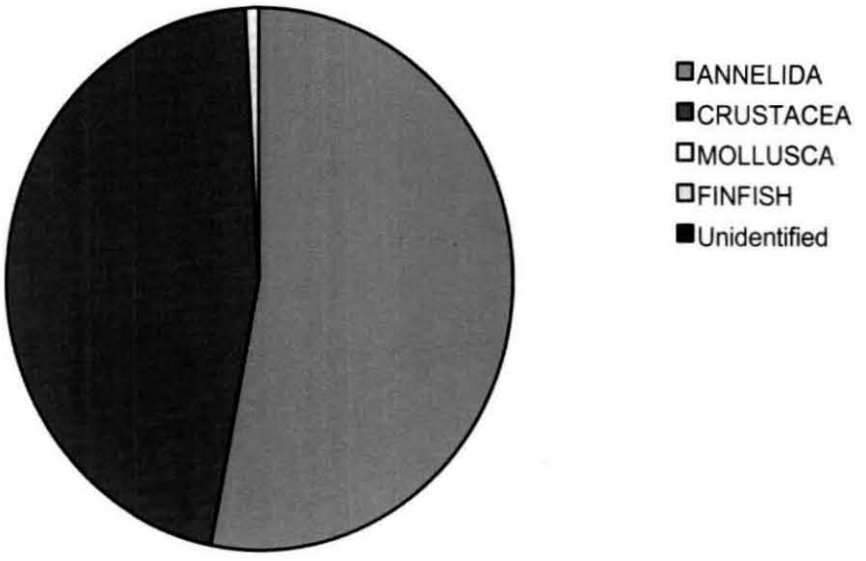

Figure 28a. Percentage abundance of different benthic macrofaunal groups at farm site of CH2

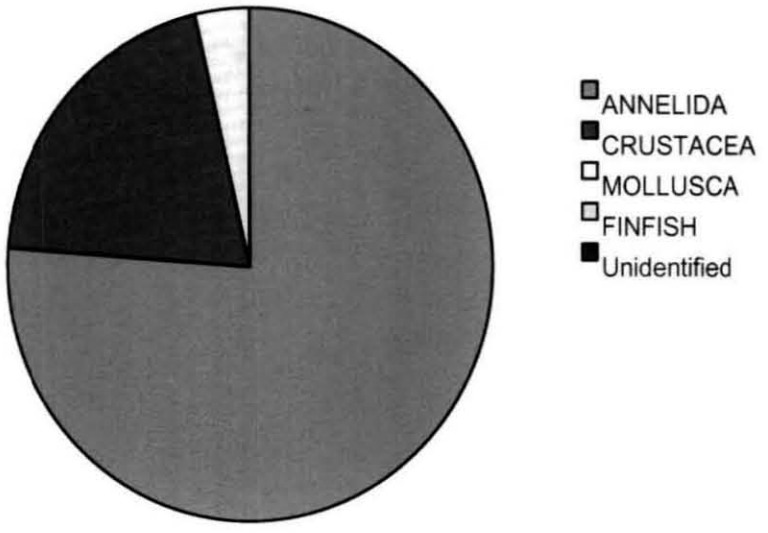

Figure 28b. Percentage abundance of different benthic macrofaunal groups at reference site of CH2

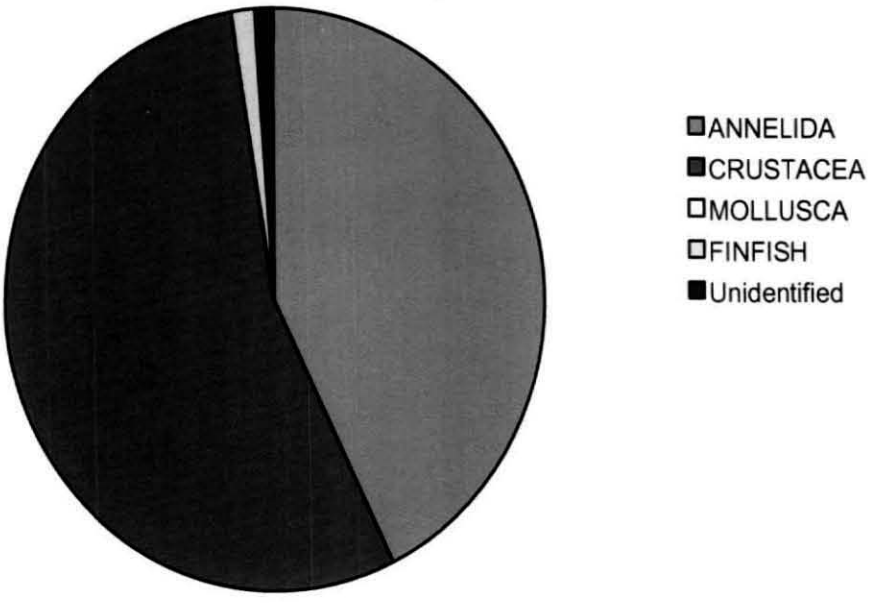

Figure 29a. Percentage abundance of different benthic macrofaunal groups at farm site of CH3

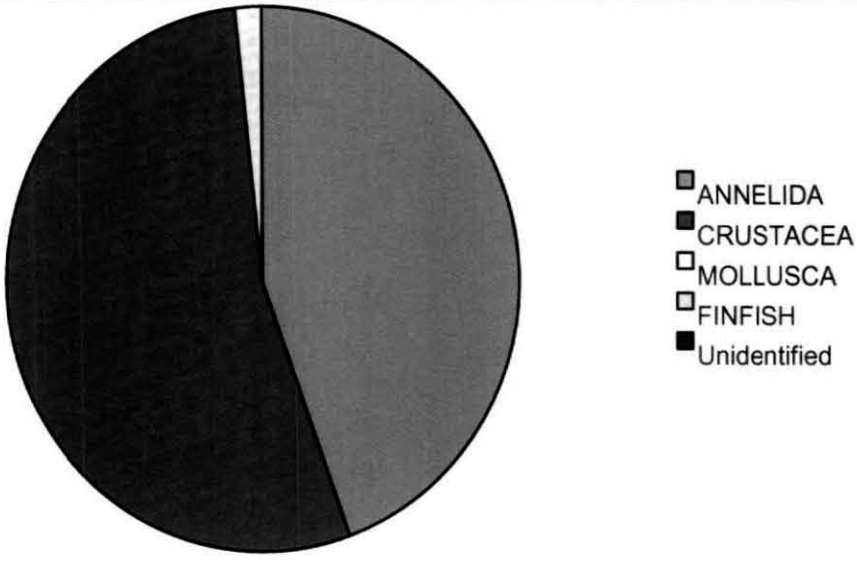

Figure 29b. Percentage abundance of different benthic macrofaunal groups at reference site of CH3

5. DISCUSSION

5.1 Impact of Oyster Culture on Hydrographic Parameters

Changes in water composition are mainly due to removal of suspended solids from the water and excretion of soluble waste products back into it. Natural populations of bivalves are known to control phytoplankton blooms, reduce total suspended solids through filter feeding (Cloern, 1982; Officer et al., 1982; Hammer, 1996; Soto and Mena, 1999) and recycle and remove organic nutrient in the water column (Doering and Oviatt, 1986; Rice 1999). However, there is little information on the impacts aquacultured bivalves have on the environment except for a few studies on mussels and northern quahog (Dahlback and Gunnarsson, 1981; Kaspar et al., 1985, Mojica and Nelson, 1993; Hammer, 1996; Grant et al., 1995; Kaiser et al., 1996, 1998). Studies have also suggested that benthic bivalves are important facilitators of regenerating inorganic nutrients (Doering et al., 1986; 1987; Dame et al., 1991; Dame and Libes, 1993). Filtration by oysters may improve water quality by reducing suspended sediment and nutrients in aquatic systems (Gerritsen et al., 1994; Brumbaugh et al., 2000; Mann, 2000). Through active filtration, oysters remove suspended particles >3µm from the overlying water column, thus reducing the concentrations of suspended sediments, detritus, and particulate-bound nutrients in estuarine environments (Bayne and Hawkins, 1992; Gerritsen et al., 1994; Brumbaugh et al., 2000; Mann, 2000).

Suspension feeding by oysters can reduce local concentrations of suspended solids, carbon, and chlorophyll a and elevate ammonia levels (Dame 1976; Dame et al. 1984, 1986, 1992; Nelson et al. 2004). But in the present investigation consistently higher total suspended solids and chlorophyll a values were recorded for the farm sites of all the farming durations compared to the corresponding reference site values The ammonia levels were less at the farm sites in contradiction with the reported results. The potential ecosystem effects of bivalve grazing support previous literature reports that populations of suspension feeding bivalves can exert top-down control on phytoplankton production in estuarine and coastal waters (blue mussels, Riemann et al. 1988; Prins et al. 1995; Pacific oysters, Souchu et al. 2001; and non native bivalves in san Francisco Bay, Cloern, 1982; Officer et al. 1982). Conversely,

some investigators contend that bivalves may not reduce phytoplankton levels appreciably. This is based on their observations of high rates of nitrogen excretion by bivalves, nitrogen regeneration to the water column from bivalve biodeposits, and either estimates or direct measures of higher primary production and phytoplankton biomass associated with bivalve grazing (Doering et al. 1986; Prins and Smaal, 1990; Asmus and Asmus, 1991; Dames and Libes, 1993; Yamomuro and Koike, 1993). The nitrogen released directly by the bivalves and regenerated from their biodeposits comes not only from ingested phytoplankton but also from nonphytoplankton material, such as nitrogen rich bacteria and flagellates (Asmus and Asmus, 1991) that are readily captured and digested by bivalves (Bayne and Hawkins, 1992). The regenerated dissolved inorganic nitrogen will stimulate phytoplankton production, hence explaining the enhanced primary production observed in the vicinity of the bivalves. Pietros and Rice, (2003) based on the stocking densities and daily water exchange rates studied concluded that aquacultured oysters had little effect on several environmental parameters, but they did affect the phytoplankton species composition and sedimentation. Based on rates of ammonia excretion by oysters and observed steady states of ammonia and other forms of inorganic nitrogen in mesocosm tanks, Pietros and Rice, (2003) hypothesized that ammonia generated by oysters is taken up by rapidly regenerating phytoplankton in the water column. The same hypothesis holds good for the present investigation also. The rapidly regenerating phytoplankton may have been stimulated at the farm sites thereby accounting to increased TSS, chlorophyll a and dissolved oxygen values. The hydrographic parameters such as temperature, pH, salinity, nitrite, nitrate, phosphate are in conformity with those of Nair et al., (1983, 1984); Nair & Azis, (1987).

Sediments regulate the production (fluxes) and the standing stocks (concentrations) of nutrients in the water (Kasper et al., 1985; Hammond et al., 1985). Mazouni et al., 1996, studied the nutrient and oxygen exchanges at the water - sediment interface in a shellfish farming lagoon (Thau, France). They measured fluxes of inorganic nutrients and oxygen over a period of one year at two stations; one located under oyster culture table, which is being subjected to intensive accumulation of organic matter and other located outside the area. The oxygen content in the overlying water was higher outside the culture areas than under the culture tables. However, for the two stations, the inorganic nitrogen contents of the

water column (whatever the chemical form, i.e., nitrate-nitrites or ammonium) were similar. The dissolved inorganic phosphorous concentrations were also similar at the two stations. In the present investigation also the phosphate, nitrite and nitrate concentrations did not vary much between farm and reference sites of different farming and crop holiday periods.

Changes in water quality have been detected in water passing through a shellfish farm, with both ammonical nitrogen and inorganic phosphorous levels increasing (Meikle and Spencer, 1992). There are reports of large ranges of fluxes for many of the same nutrients both within the same study site and among sites; therefore, the impacts of bivalve culture on coastal nutrient dynamics is poorly understood and difficult to quantify (Dame and Danker, 1988; Hatcher et al., 1994).

5.2 Impact of Oyster Culture on Sediment Characteristics

In the present investigation also the farm sites had more of fine sediments i.e., silt and clay when compared to the reference sites. The percentage of coarse sand and fine sand decreased with increasing period of farming. Percentage organic carbon values also increased with the increasing period of farming.

Benthic environmental impacts may arise from the deposition of solid wastes from the molluscs growing on the structures (longlines, raft/racks). Solid wastes from bivalve culture comprise organic faeces and pseudofaeces, shells and other detritus discarded or dislodged from the farm (NCC, 1989). These wastes can potentially alter the physical character of the sediment; alter nutrient cycling in the sediment. In areas with high densities of shellfish culture and low tidal flushing, this can lead to an accumulation (or concentration) of organic matter in the sediments and the enhancement of benthic fluxes of nutrients (Souchu *et al.*, 2001).

The impact of bivalve culturing is related to the intensive biodeposition of the faeces and pseudo-faeces that modify the physical and chemical characteristics of the benthic environment as they accumulate in the bottom sediments (Kasper *et al.*, 1985; Gilbert *et al.*, 1997; Mirto *et al.*, 1999b). Chamberlain, *et al.*, (2001) considers that one important factor determining the final fate of faecal matter, and any subsequent impact, is the dispersion of biodeposits from the farm site.

Several authors have reported that mussel farming is known to be responsible for intensive biodepostion of faeces and pseudo-faeces that might cause strong changes in the physical and chemical characteristics of the sediments beneath the culture structures. This enrichment has been reported to change the characteristics of the sediment under farms (Dahlback and Gunnarsson, 1981; Kasper *et al.*, 1985). They found that the sediment under mussel cultures had a finer texture, lower bulk density and higher water content than those at adjacent stations. Mattson and Linden (1983) also found sediments under mussel farms to be slightly finer and in addition noted that they had a higher organic content and a negative redox potential when compared to reference sites. Kirby, (1994b) reported that sedimentation beneath the farms will not only be due to organic enrichment but also be due to the presence of artificial structures within the water body which provides an impediment to the flow. Anything which slows the flow of water will cause it to drop part of its sediment load therefore increasing the amount of sedimentation.

The findings of the present investigation confirms to the views of Dahlback and Gunnarsson, 1981; Kasper *et al.*, 1985; Mattson and Linden (1983); Kirby, (1994b). The increase in silt, clay and organic carbon percentages may partly be explained by the organic enrichment that has taken place due to continuous farming at the same site. The maximum depth recorded in the Ashtamudi estuary is only 3.14 m which is attainable at high tide levels (Nair et al. 1984; Nair and Azis, 1987). With this depth sediment resuspension may not place as the currents generated will not be sufficient enough to result in dispersal of biodeposition. As suggested by Kirby, (1994b) the farm structures and oyster strings of the present investigation might have obstructed the free flow of water currents through the farm site thereby aiding sedimentation and organic enrichment.

Biodeposition from pseudofaecal and faecal production by *C. gigas* and the resulting chemical changes in both sediment and the overlying water column have been extensively studied by Deslous-Paoli *et al* 1987, 1992, Sornin *et al.* (1983). Nugues *et al.* (1996) noted an increase in organic and silt composition sediment beneath the trestles. In this case water velocity was noticeably decreased by the presence of trestles which probably lead to the increase in sedimentation rate observed beneath them. Cho *et al.* (1982) found great quantities of organic matter

and sulphides in the bottom mud of shellfish (unidentified species) in the innermost part of Jinhae Bay, Korea. Other studies have shown that trestle cultivation of oysters is responsible for increased sedimentation of both organic matter and contaminants (Martin *et al.*, 1991; Kirby, 1994b). Sornin *et al.* (1983) went as far as to say that the accumulation of biodeposits by oysters brings about noticeable geological modifications of the underlying sediment. He recorded an increase in the organic, silt and phaeopigment content beneath the trestles which was again probably related to the recorded decrease in current velocity at both sites (Sornin *et al.*, 1983).

Even though natural sedimentation rates were not quantified in the present study, it can be proved with the organic carbon content of reference sites that increased accumulation of fine sediments and organic matter at farm sites is not due to the natural sedimentation but due to the organic enrichment taking place due to oyster culture and obstruction of farm structures in sediment dispersal. Martin *et al.* (1991) looked at the significance of oyster biodeposition in concentrating organic matter and contaminants in the sediments. The results showed that biodeposition leads to sedimentation of matter which can reach 700 $g.m^{-2}.J^{-1}$ and 500 $g.m^{-2}.J^{-1}$ on a sandy shore and in a clay bottomed pond respectively. Sedimentation results in organic matter and chemical contaminants accumulating on the seabed. The impact was particularly noticeable in the sandy sediment, and was observed down to a depth of 25 cm. Due to the washing of sand, the vertical profiles of organic matter and contaminants in the foreshore sediment became similar to those observed in the reference sediment two months after stopping the oyster rearing and so the biodepositon. In contrast, Cho and Park (1983) looked at eutrophication of bottom mud in Goseong – Jaran Bay, Korea, an off-bottom oyster and arkshell fishery and found no change in status since 1976. However in the present investigation the crop holiday period did not result in improvement over the sediment characteristics nearer to that of initial farming periods or reference site values. This could be due to the fact that during crop holiday periods only the oyster stock was harvested and the entire farm structure was left as such. The farm structure might have obstructed the free flow of water through the farm and continued to aid in sedimentation rather than dispersal.

Nugues *et al.*, (1996) report that the presence of trestles has been noted to decrease water velocity causing increased sedimentation. Their presence may have the effect of causing the water body to slow down and deposit more of its sediment load. At high densities, *C. gigas* generates biodeposits, which leads to reduced particle size and increased organic content in sediment (Castel *et al.* 1989).

Crawford *et al.*, (2001a) investigated the effects of shellfish farming on the benthic environment at three long-established subtidal oyster and mussel farms that had had relatively high levels of production. Their overall results indicated little effect of shellfish farming within the lease, and no impacts outside the lease boundary. Similar view have been expressed by Crawford et al., (2003)

Excess biodeposition, especially in low water flow environments, has the potential to stimulate bacterial respiration to such an extent that the sediments become anoxic, thereby inhibiting coupled nitrification – denitrification and causing sediment-bound P to be mobilized. Such local adverse effects can be ameliorated by moderated water currents or wave action that allows biodeposits to be spread across a larger bottom area and that mix oxygen from the surface to the bottom waters (Haven & Morales – Alamol, 1968; Dame *et al*, 1991). The adverse effects of sediment overenrichment by bivalve biodeposits have often been observed in sediments underlying bivalves in suspended raft culture (Ito and Imai, 1955). Tuttle and Jonas (1992) also observed elevated amounts of microbially labile organic matter in surficial sediments beneath eastern oysters grown in floats in Chesapeake Bay. These findings suggest that extremely dense bivalve communities can adversely affect sediment microbial processes by shifting them form aerobic to anaerobic metabolism as result of increased particulate organic matter loading.

Based on findings of the present study and previous studies it can be concluded that even with low density oyster culture if undertaken in a relatively shallow regions with poor flushing conditions, significant changes in sediment characteristics are inevitable.

5.3 Impact of Oyster Culture on Benthic Macrofauna

Studies carried out on benthic community changes associated with intertidal oyster culture are very few and this investigation is the first account on impact assessment of Indian edible oyster culture. Summarized information on environmental impacts associated with oyster culture in France is available from the work of Castel *et al* (1989); in UK from the work of Nugues *et al.* (1996); and in USA from the work of Simenstad and Fresh (1995).

In the present study the annelid *Capitella capitata* was consistently present at all farm sites except F3 sites and the average abundance at reference sites (F1, F4 and F5) sometimes even exceeded that of farm sites indicating that this species was ubiquitously distributed and that it could not be considered as an indicator of organic enrichment as suggested by Pearson and Rosenberg, (1978); Dahlack and Gunnarsson, 1981. The average annelids abundance decreased with the increasing period of farming. Similarly the crustacean group abundance also decreased with increasing period of farming suggesting that these two groups are more sensitive to organic enrichment and increased sedimentation rates. Such changes in benthic communities under shellfish farms have been documented in Tenore et al., 1982; Cho, 1991; Findlay et al., 1995; Grant et al., 1995; Stenton-Dozey et al., 1999. Benthic community shifts associated with an increase in organic and silt composition beneath the oyster trestles have been reported by Simestad and Fresh (1995) and Nugues et al., (1996). In the present study also increased organic carbon content, silt and clay composition was observed and this changed environment may have influenced the abundance of benthic macrofauna.

The molluscan group abundance was seen only at reference sites and the finfish group was present only in farm sites. Studies of Iglesias, 1981; Romero et al., 1982; Lopez-Jamar et al., 1984; Gonzalez-Gurriaran, 1986; Freire et al., 1990 suggest that certain types of macrofauna, such as crabs and demersal fishes, benefit from the additional food supply associated with fall off of bivalves from growing structures as well as from the increase in the population of deposit-feeding prey organisms. The *Gobiodes* sp found in the present study may have been attracted towards the farm sites due to the increased food availability at these sites.

Organic enrichment of the sediment directly under the bivalve culture will have an additional local impact on the benthic faunal biomass and biodiversity. The impact on a particular site will depend on the type of sediment, current velocity and the species present. Biodeposition by bivalves generally provides a strong input of organic matter of high quality to benthic assemblages. Organic loading in the marine environment usually result in an increase in sediment oxygen demand by benthic microorganisms and fauna, and subsequent depletion of oxygen in porewater and near bottom water (Pearson and Rosenberg, 1978). According to Gray et al. (1992), depletion of dissolved oxygen in the interstitial waters of organically enriched sediments results in the mortality or emigration of most species characteristic of undisturbed sediments. Increased benthic microbial activity will often result in oxygen depletion and low macrofaunal diversity as shown by Mattson and Linden (1983) and Kasper *et al.* (1985).

Pocklington *et al.* (1994) looking at the polychaete response to different aquaculture activities at several sites in Canada, concluded that the polychaete species *Nephtys neoten* dominated the fauna beneath the mussel lines and the sediments beneath the shellfish lines were black, finely pelleted and had high organic content. Nugues *et al.* (1996) noted small, but significant, changes in the macrofauna commuity sampled beneath oyster trestles, compared with that found in adjacent uncultivated areas. These changes were attributed to an increase in organic and silt composition and a reduction in the depth of the oxygenated layer of the sediment beneath the trestles. They also noted that the main factors affecting the macrofaunal communities appeared to be linked to environmental parameters such as sedimentation rate and current velocity.

The works of Heral *et al.*, 1986; Castel *et al.*, 1989 have conclusively proved that if there is organic enrichment of the sediment then there is likely to be some detectable change in the benthic fauna. The organic rich oyster deposits favour meiofauna by increasing the trophic resources but do not favour macrofauna by inducing low oxygen concentrations. Declines in the abundance and species diversity of the burrowing and deposit-feeding macrobenthic organisms (bioturbators) have been observed by Tenore *et al.*, 1982, Rodhouse and Roden, 1987.

Recent environmental studies of intertidal and subtidal oyster culture in Tasmania did not indicate any negative impacts on sediment biochemistry of macrofauna (Thorne, 1998; Crawford et al., 2003). Thorne (1998) found that intertidal oyster culture areas in Tasmania had a higher species number, diversity, and the abundance than reference areas. Similarly, Dealteris et al. (2004) observed that oyster cages placed on the seabed supported a significantly higher abundance of organisms per m^2 than either reference areas with aquatic vegetation or non-vegetated seabed. Nugues et al., (1996) detected small but significant differences in the macrofuanal community located directly below oyster tables compared to that found in adjacent uncultivated areas. In contrast, significant decreases in macrofaunal abundance have been documented in areas of extensive intertidal oyster culture in France (Castel et al., 1989). In the present study higher species number and diversity was found only at farm site of F1 and in all other sites, the number of species and diversity was low contradicting the results of Thorne, (1998).

Moore, (1996) looked at the impact of an intertidal oyster farm on the benthos in Dungarvan Harbour. She compared the benthos at the control site to that at the site with the oyster trestles (under the trestles and in the servicing lane between trestles). Shannon-Weiner index of the fauna beneath the trestle was found to be less diverse that the control but surprisingly the fauna in the lanes between trestles was more diverse than control. Moore, (1996) suggested that differences in all three species may be due to mechanical disturbance rather than organic enrichment. Sammy De Grave *et al.* (1998) also suggested that the changes in benthic macrofauna did not associate with intertidal oyster Crassostrea gigas (Thunberg) culture is not due any form of organic enrichment, as elevated levels of organic enrichment were encountered nor were potential organic enrichment indicator species, such as *Capitella capitata* encountered in densities usually associated with organic enrichment.

Multivariate analysis of benthic macrofaunal community clearly showed dissimilarity of species abundance at different sites under farming and crop holiday periods. Maximum dissimilarity between farm and reference sites of F1, F2, F4, crop holiday sites was observed with respect to *Gammarus* sp. High numbers of this species were found at reference sites when compared to the farm sites. Silt and clay

fractions of sediment found at the farm sites may have restricted the abundance of *Gammarus* sp. High organic carbon values found at the farm sites also corroborate this hypothesis.

Mallet et al., (2006) were of the opinion that environmental impacts of shellfish vary depending on the scale of culture, the culture method and the prevailing environmental conditions. The variable results reported in the literature illustrate the importance of the interaction between the particular grow-out structure, the intensity of culture and the local environmental characteristics (Castel et al., 1989).

SUMMARY

- Environmental impacts due to suspended oyster, *Crassostrea madrasensis* (Preston) culture were assessed during one (F1), two (F2), three (F3), four (F4) and five (F5) years of farming as well as after three (CH1), six (CH2) and nine (CH3) months crop holiday periods.
- Impact assessments were made on hydrographic parameters, sediment characteristics and benthic macrofaunal community changes. The results of farm sites of varying farming and crop holiday periods were compared with that of reference sites.
- No significant differences in hydrographic parameters such as temperature, salinity, pH, total suspended solids, ammonia, phosphate, nitrite, nitrate, chlorophyll b, and chlorophyll c were observed between farm and reference sites of any farming or crop holiday period or between farming and/or crop holiday periods. However elevated levels of total suspended solids were more noticeable at farm sites than the reference sites.
- Significant differences in respect of dissolved oxygen, chlorophyll a and phaeopigment values were found between farm and reference sites. The differences were attributed to the low levels of ammonia, and the rapidly regenerating phytoplankton.
- Impacts on sediment characteristics such as percentages of coarse sand, fine sand, silt, clay and organic carbon in upper 5 cm and 5 – 10 cm portions of sediment were assessed. There were no significant differences between upper 5 and 5-10 cm potions of the sediment excepting that of organic carbon.
- The percentage coarse and fine sand fractions of in upper 5 cm portion of farm sediments decreased with increasing periods of farming. The percentage coarse sand fraction was more in the first year farming period and almost 50 % reduction in coarse sand percentage was noticeable at the end of five year farming period. The fine sand fraction was also reduced by 20% by the end of five year farming period.
- The percentage silt and clay fractions in upper 5 cm portion of farm sediments increased with increasing period of farming. The % silt in one year farming site

was 12.34 ± 0.70 and it increased to 17.35 ± 1.90 by the end of five year farming period. Almost 80% increase from the initial clay fraction percentage of 11.32 ± 1.10 was observed by the end of five year farming period.

- The mean percentage organic carbon in upper 5 cm portion of farm sediments was 0.87 ± 0.04 in the first year farming period and it increased (about 42%) to 1.24 ± 0.13 by the end of fifth year farming period.
- Crop holiday period had no positive influence on the sediment characteristics studied. The observed trend was similar to that of farming periods.
- Assessment of benthic macrofaunal communities revealed that the average abundance of annelid and crustacean groups decreased with the increasing period of farming. Mollusca group was seen only at reference sites and the finfish group was present only at farm sties.
- Highest Shannon diversity and Margalef species richness indices were recorded from farm sites of F1 and lowest from F3 farm sites. The Shannon diversity and Margalef species richness indices were almost same for all the farm sites under crop holiday periods
- Trends in restoration of benthic macrofaunal communities were noticeable in sites under crop holiday periods
- Maximum species similarity percentage was observed within farm and reference site of F3 and maximum dissimilarity percentage was recorded between farm and reference sites of F4.
- In ANOSIM the Global R statistic values indicated absolute difference in macrofaunal species abundance of farm and reference sites of F3. Significant differences in macrofaunal species abundance was also observed between farm and reference sites of F4, F5, & CH3.
- SIMPER analysis showed that the amphipod *Gammarus* sp contributed to maximum dissimilarity between the farm and reference sites of F1, F2, F4, CH1, CH2 & CH3. therefore Gammarus sp can be considered as an indicator species for rapid assessments of impacts of oyster farming in Ashtamudi Lake ecosystem.

- The findings of the present study implicate that even low density oyster culture, if undertaken in a relatively shallow regions with poor flushing conditions, significant changes in sediment characteristics and benthic macrofaunal communities are inevitable
- Based on findings of the present study it is recommended that oyster farming can be done continuously only for a maximum period of two years and if the culture needs to be carried for more than two years at the same site, a crop holiday of at least six months is to be given. Alternately, the location of farming has to be shifted to an adjacent site after 2 years.
- During crop holidays, it would be advantageous ecologically if the bivalve growing structures are removed from the farm site in order to avoid impediments to sediment dispersion.

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