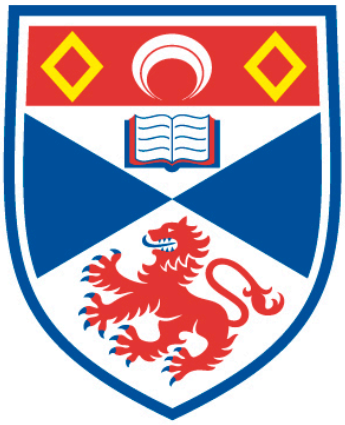
BENTHIC FORAMINIFERA AS A NOVEL BIO-MONITORING TOOL IN THE ASSESSMENT OF ENVIRONMENTAL IMPACTS LINKED TO MARINE AQUACULTURE

Montaha Alammar

A Thesis Submitted for the Degree of MPhil
at the
University of St Andrews



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ABSTRACT

The present thesis describes the behaviour of benthic foraminiferal species in response to various levels of natural and/or anthropogenic organic matter enrichment in the benthic environment. Loch Creran, on the west coast of Scotland, was chosen as representative of such environments, with both organic matter accumulation from natural sources and an active marine aquaculture industry. An improved, quantitative understanding of foraminiferal response to the variation in benthic environmental gradients associated with fish is established. Furthermore, the performance of these foraminiferal species as a novel bio-monitoring tool to assess the impact of marine aquaculture is evaluated. In order to address how aquaculture has influenced the benthic environment at Loch Creran, foraminifera, sediment grain-size, organic matter (OM) content and abundances were analysed in surface samples collected from beneath and around floating fish cage complexes. In this study, we followed the Foraminiferal Bio-Monitoring (FOBIMO) protocol (Schönfeld. et al., 2012), which proposed a standardised methodology of using foraminifera as a bio-monitoring tool to assess the quality of the marine ecosystem and applied these protocols to the rapidly expanding marine aquaculture sector in Scotland.

The thesis quantified the potential of benthic foraminifera for use in reconstructing paleoenvironments from areas the pre-impacted environmental status in areas exposed to environmental stress (e.g. accumulation of organic matter) following the onset of marine aquaculture. Twenty stations were sampled within Loch Creran to describe the spatial and down-core (temporal) distribution pattern of benthic foraminiferal assemblages. For the spatial distribution study,

triplicate, Rose-Bengal stained samples from an interval of (0_1cm) below the sediment surface were studied at each station from below the fish cages (impacted stations) to a distance of over 1 km from the farming sites and from the upper basin, where fish caged are absent and a natural source of organic matter exists from the River Creran. Morphospecies counts were conducted, and the organic carbon and the grain size distributions determined. For the down-core study, two short sediment cores, SC-02-A and SC-04-B were examined to present the fish farming site and a more distant, non-fish farming site. The two cores were analysed to assess the temporal (down-core) changes in benthic foraminiferal distribution. The total organic matter (TOM) content was determined and indicates temporal changes in OM accumulation rate and associated benthic foraminiferal responses.

The results indicated 4 foraminiferal assemblage groups within the surface sediments: (i) A1 (the reference site), (ii) A2-1 (non-fish farming sites), (iii) A2-2 (fish farming sites) and (iv) the upper basin assemblage group (River Creran). The assemblages were found to be well adapted to a high input of OM contents and a minimum dissolved oxygen (DO2) penetration depth into the sediment. The majority of foraminiferal species at the impacted sites were agglutinated species (e.g. *Eggerella scabra*), likely related to the presence high sediment (OM) contents and low dissolved oxygen concentrations. Down-core distribution data indicated that a faunal shift has taken place, correlating with changes in OM enrichment in the sediment. The species diversity of foraminifera decreases above this OM enrichment horizon in the fish farming core. Specimens of *Ammonia beccarii* were dominant in the lowermost sediment core (i.e. the pre-impacted sediment). Above 7 cm, the

assemblages change and become dominated by *Eggerella scabra*, coinciding with a marked change in sediment colour. The results of this study highlight the potential of using benthic foraminifera as reliable indicators of pre-impacted marine habitats, with great potential to understand environmental history around the globe.

General acknowledgements

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INTRODUCTION AND LITERATURE REVIEW

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INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Foraminifera are single celled organisms which live predominantly in the marine environment and constitute the most diverse group of shelled microfauna in marine environments (Sen Gupta and Machain-Castillo, 1993; Goldstein, 1999). There are three main groups of foraminifera recognized based on habitat: those that live freely in the water column (planktonic); those that live attached to substrates (benthonic); and those that dwell within the sediment itself (infaunal benthonic). They have a global distribution, inhabit a diverse range of habitats and are one of the most successful groups of protozoa (Lee, 1980). They have been used extensively in different fields. Foraminiferal research typically lies at the border between the biological, environmental and Earth sciences. They are marine organisms and typically represent a major component of marine communities, being highly sensitive to environmental influences, and the most abundant organisms preserved in the deep-sea record (Gooday, 2003). They also constitute a significant component of the coastal benthic communities (Murray, 2007) and play an important role in global biogeochemical cycles of inorganic compounds, making them one of the most important animal groups on Earth (Anderson, 1988; Haynes, 1981; Lee and Anderson, 1991b).

Their tremendous taxonomic diversity gives them the potential to exhibit biological responses to various pollutants, which in turn adds to their potential as index species for monitoring pollution from diverse sources. In turn, changes in foraminiferal community structure are particularly responsive to environmental change. Foraminiferal tests are readily preserved in most marine sediments and can record evidence of environmental stresses through time, thus providing historical baseline data even in the absence of background environmental monitoring studies. They are small (typically < 1mm) and abundant compared to other hard-shelled taxa (such as molluscs which are often used for pollution monitoring), which makes them particularly suitable to recovery in statistically significant numbers from relatively small sediment samples. Individuals (and populations) are characterized by a rapid individual growth (Walton, 1964) and a they have short, typically annual or sub-annual, reproductive cycle (Boltovskoy, 1964; Yanko et al., 1999; Murray, 2006, p. 32). Current estimates of foraminiferal life spans range from three to four months for smaller foraminifera in temperate shelf seas, and from six months to 2 years for larger foraminifera in warm tropical seas (Murray, 1991).

Foraminiferal assemblages often show species-specific responses to environmental conditions (Fursenko, 1978). They have biological defense mechanisms (Yanko *et al*., 1994a) which protect them against unfavourable

environmental factors, thus providing detectable biological evidence of the effects of, for example, pollution. They are often considered in the environmental sciences as one of the organisms most suitable to behave as indicators of environmental conditions (Debenay et al., 2001; Armynot du Chàtelet et al., 2004; Albani et al., 2007; Eichler et al., 2012). These characteristics make them powerful tools for continuous biological monitoring of marine environments (Yanko et al., 1999), and important tools for reconstructing past ocean conditions (Gooday,2003).

1.2 Foraminifera history

The first record of fossil foraminifera was reported by Herodotus (5^{h} Century BC) from limestone blocks used by the ancient Egyptians during the construction of the pyramids at Gizeh. However, the first written reference to foraminifera is by Strabo, who wrote, of his observations of what we now know to be larger benthic foraminifera, (LBF), *Nummulites gizehensis.* There may be said to have been two, partially overlapping, phases of past research on the foraminifera, namely, the descriptive and the interpretive (Jones, 2014).

The descriptive phase began with the first formal descriptions of species of foraminifera dating back to the late eighteenth to nineteenth centuries. Those undertaken by the so-called 'Continental School', personified by the great French naturalist Alcide Dessalines d'Orbigny,

forming a narrower, or 'splitting', species concept than would be widely accepted today. While those undertaken by the 'English School', personified by Henry Bowman Brady, used a wider, or 'lumping' concept. The earliest classification schemes were undertaken by the likes of d'Orbigny and Brady in the nineteenth century (Jones, 2014).

The interpretive phase began with the first use of foraminifera in biostratigraphy in the late nineteenth century, when Josef Grzybowski applied them in the oilfield area of the Polish Carpathians (Charnock & Jones, in Hemleben et al., 1990; Kaminiski et al., 1993). Their use continued with further applications in the petroleum industry, in areas as diverse as California, the US Gulf Coast, Iran, Nigeria, Papua New Guinea and Sarawak, in the early twentieth century (Jones, 2014). In the following section, aspects of foraminiferal biology are discussed in term of their test morphology and taxonomy.

1.3 Foraminiferal biology

1.3.1 Test morphology

Foraminifera possess a test or shell that surround the species and separates it from the surrounding water mass. There are numerous foraminiferal test (shell) forms which shows great divergence in their morphology, sometimes even within a single species (Lee *et al.*, 1991). Morphology of foraminifera is considered as an adaptive characteristic

(Hallock et al., 1991). The great variety of test forms suggests that many taxa are exceptionally well adapted for particular environments (Marszalek et al., 1969, Hallock et al., 1991). Foraminifera build an amazing variety of tests forms that range from simple tubes or spheres to complex multichambered forms (Lipps, 1973). The test usually reflects the life habits of the species, hence, understanding the morphological variability in benthic foraminifera is crucial to the interpretation of different environmental conditions under which they lived, including temperature, salinity, depth and dissolved oxygen content (Boltovskoy and Wright, 1976; Haynes, 1981; Murray, 1991, 2006). Therefore, observations on these morphological changes may allow us in certain aspects to better understand and interpret the fossil record (Boltovskoy et al., 1991). Furthermore, the test enables foraminifera to tolerate changes in stressed environmental conditions and provides highly efficient ways of adapting these environmental changes (Marszalek et al., 1969). In this way, the tests of foraminifera provide essential information for understanding past environmental conditions (paleoenvironments) (Gould, 1970; Schulter, 2000).

Foraminiferal tests are composed of several types of material (Loeblich and Tappan, 1964). The wall composition of foraminiferal tests is typically maybe organic, agglutinated (constructed of foreign particles and cemented together by the organism), or comprised of calcium carbonate

(CaCO3) (Hemleben et al., 1986, Goldstein, 1991). In general, benthic foraminifera can be classified as one of three groups (Textulariina, Miliolina and Rotaliina) which correspond with agglutinated, porcellaneous and hyaline test wall structures, respectively (Leoblich and Tappan, 1964). Agglutinated test forms of benthic foraminifera consist of accumulated mineral particles cemented together within an organic material (Anderson & Lee, 1991). Particles often appear to be random collections of available material in the environment, but some species show selective in selection of particle size, composition and shape (Lipps, 1973; Anderson & Lee, 1991). Calcium carbonate forms are composed of either magnesium calcite, calcite or aragonite (Hemleben et al., 1986). The composition of the wall structure makes foraminifera more advantageous to live in particular environment than other (Hallock et al., 1991). Therefore, the wall structure of the shell can determine where various species can survive (Scott et al., 2001).

1.3.2 Taxonomic history

Since foraminifera are primarily delineated using their morphological features, it is important to create a reliable taxonomic scheme to distinguish between their variable forms. The classification of foraminifera has a deep-rooted history going back to the beginning of the 19th century and a diverse range of classification schemes and diagnostic features have been used to classify foraminifera over this time period. The earliest studies dating back

over two millennia to the description of Herodotus and Starbo (425 – 63 BC), who noted foraminifera as lens-shaped objects in the limestone blocks of the pyramids (Cifelli, 1990) and grouped them separately from other protists. This was followed by the classification of Alcide d'Orbigny (1826), who treated foraminifera as distinguishable individuals and grouped them by their growth pattern. D'Orbigny established the order foraminifera, provided the first descriptions of these species and proposed the first taxonomic system based on the growth plan of foraminiferal tests (reviewed in Cifelli, 1990). A diverse range of classification schemes followed this classification system of D'Orbigny. The subsequent foraminiferal classifications were based on the differences in the form of the chamber arrangement. One of these classifications described by Schultze (1854), who grouped the individuals based on differences in chamber structure e.g., single chamber vs multi-chambered foraminifera. In addition, the presence or absence of pores was used in early classification schemes (Reuss, 1861; Carpenter et al., 1862). Later, this was progressively replaced by a classification based on the presence or absence of pores, which was also assigned taxonomic weight by early classification schemes (Reuss, 1861; Carpenter et al., 1862). Historically, wall composition of foraminifera was considered to be one of the most diagnostically significant features (Williamson, 1858; Pokorny, 1963).

Differences in the foraminiferal test (wall) composition and related characteristics gained greater importance over time and eventually became the main standard rule to distinguish higher-level groups in foraminifera and one of the most diagnostically important morphological features (Williamson, 1858; Brady 1884; Loeblich and Tappan, 1964). Williamson (1858), for example, provided a detailed description of several taxa (especially unilocular species). Brady (1884) described the species of foraminifera recovered from the Challenger expedition, which formed the basis of an updated taxonomy by Jones (1994). Jones (1984a and b) produced a taxonomic description of Late Quaternary benthic foraminifera from the Porcupine Bank region as part of a PhD thesis.

During the early part of the 20th century, Joseph Cushman produced a taxonomic framework for benthic foraminifera recovered from North Atlantic sediments (i.e. Cushman 1911, 1923, 1940). Further new species were described by Phleger et al. (1953) and Barker (1960). Murray (1971) also contains plates and descriptions of some important taxa. Hermelin and Scott (1985) provided plates and morphological descriptions of 63 taxa from the central North Atlantic. Schönfeld (2006) is a detailed study of the biogeographic distribution of different taxa in the NE North Atlantic. Schweiger (2006) provides a detailed taxonomic assessment of specific species. Gooday and Hughes (2002) supply plates and descriptions of some

of the smallest taxa. For a more detailed history of foraminiferal classification refer to Cifelli (1990).

It is also worth mention that there have been various attempts to identify foraminifera using different approaches, rather than their morhospecies characteristics. One of these approaches to foraminiferal classification was published by King and Hare (1972) who analysed the amino acid composition of the tests of sixteen species of foraminifera. The hypothesis of this work was to analyse the amino acids in the calcified tissue to determine if they varied in a systematic manner and whether or not they paralleled morphology, thus reflecting a classification based on morphology. The study demonstrated that each morphospecies had a distinct amino acid composition that differed from the other morphospecies analysed (Yanko et. al., 1999. More recently, molecular biology has been used to develop and define benthic foraminiferal taxonomy (e.g., Hayward et al., 2004; Schweizer et al., 2005, 2009, 2012; Pillet et al., 2013; Darling et. al., 2016). For example, some molecular studies have shown evidence of unrecognized genetic diversity, while other studies highlight morphological differences in the absence of supporting genetic evidence s (i.e., Darling and Wade, 2008; Pawlowski and Holzmann, 2008). Despite nearly two hundred years of endeavour, it seems that benthic foraminiferal taxonomy is still a matter of some debate.

Despite extensive taxonomic investigations by numerous researchers, the most comprehensive classification to date is that of Loeblich and Tappan (1988). The original work of Loeblich and Tappan (1964, 1988, and 1992) which defined and divided foraminifera mainly based on the morphological test types has become one of the most commonly used classification schemes in the literature. This scheme utilized the composition and ultrastructural features of the test wall, which are relevant at different taxonomic levels, to distinguish foraminifera into an order and sub-orders. The original work of Loeblich and Tappan (1964a) estimated that there were close to 100 families, over 1200 genera, and some 27,000 species of foraminifera described. This vast array of foraminiferal forms was subsequently organized and categorized into 12 sub-orders, 47 super-families, 296 families and 302 sub-families. These classifications are summarized in Loeblich and Tappan (1964a), which considered to be one of the most enthusiastic and complete classifications yet proposed.

Finally, it is important to mention that later studies have made some modifications to Loeblich and Tappan's (1992) taxonomic scheme, retaining the core structural foundation but with the addition of individually separated and distinct modifications e.g. the number of orders/classes and sub-classes recognized, but the foundations of this system remain largely unchanged (Sen Gupta, 1999; Mikhalevich, 2004; Kaminski, 2005).

1.4 Previous studies

Foraminifera are valuable indicators of natural and anthropogenic environmental stress (e.g., Alve, 1991, 1995; Yanko et al., 1999; Martin, 2000; Scott et al., 2001, 2005; Alve et al., 2009). Because of the limited mobility of the benthic fauna, they can reflect a direct response to local environmental conditions (Boltovskoy, 1964; Yanko et al., 1999; Murray, 2006, p, 32). Hence, they can be used to define present assemblages under local environmental conditions, and by comparing negatively impacted sites with reference sites, they can document historical changes in environmental status (Hallock, 2000). Their short reproductive cycles (six months to one year) (Hallock, 1985) and their rapid growth (Walton, 1964) make them suitable for registering environmental changes over short periods of time. These changes can be visible in the test itself (in morphology and/or chemical composition) or in community changes such as the occurrence or disappearance of species or changes in species abundance and species richness (Debenay et al., 2000).

The use of foraminifera developed with the establishment of the regional larger benthic and, importantly, global planktic foraminiferal biostratigraphic zonation schemes in the late twentieth century (Bolli et al., 1985). These were accompanied by improvements in the understanding of foraminiferal ecology, oceanography, palaeoecology, palaeoceanography

and palaeoclimatology, and of biogeochemical proxies (Scott & Medioli, 1980; Vincent et al., 1981; Lutze & Coulbourn, 1984; Corliss, 1985; Delaney & Boyle, 1987; Gooday & Lambshead, 1989; Berger et al., 1989; Herguera & Berger, 1991; Kaiho, 1994; Jorissen, 1999; Pearson & Palmer,2000).

1.4.1 Distribution studies

As early as the 1960s, several studies have included the distribution and abundance of benthic foraminifera to describe the state of marine environments (e.g., Resig, 1960; Watkins, 1961; Bandy et al., 1964a, b; Seiglie, 1968). Studies from marine habitats have been carried out with respect to the abundance and diversity of foraminifera in intertidal salt marshes (Lee et al. 1969; Muller, 1973; Scott and Modioli, 1978, 1980; De Rijk, 1995; Horton et. al., 1999), mudflats in estuarine locations (e.g. Buzas 1969; Allen and Roda, 1977; Murray, 1968, 1980, 1983; Alve and Murray, 1994; Murray and Alve, 2000; Alve and Murray, 2001), fjordic estuaries (Alve and Nagy, 1986), shelf seas (Murray, 1991; Scott et al., 2003) and the deep-sea (Gooday, 1986; Gooday and Rathburn, 1999).

The distribution of these species varies greatly, both spatially and temporally, over nearly all scales in polluted and non-polluted environments (Haynes, 1960, 1970; Cummins, 1979). It is therefore very important to understand the spatial distribution of benthic foraminiferal because they can record and reflect the level of pollution and a measure of overall

environmental impact. Studies have shown that foraminifera often show temporal (down-core) zonation that can be used to document pre-impacted environment (palaeoenvironment) (Bernhard, 1993; Moodely et al., 1997). This stratigraphic distribution can also be utilised for future environmental monitoring (e.g., Clark, 1971; Grant et al., 1995; Scott et al., 1995; Hallock et al., 2003).

Although the effect of each pollutant is not yet very well understood (Alve, 1995; Yanko et al., 1999; Morvan et al., 2004; Saraswat et al., 2004), their cumulative impact is particularly evident in the diversity and abundance of foraminiferal assemblages (Romano et al., 2008; Martins et al., 2010). Equally, the percentage of deformed shells, up to 20% of the total fauna, could be related to the presence of pollutants (Yanko et al., 1998; Samir et al., 2000; Martins et al., 2010; Coccioni et al., 2009). Trace elements, hydrocarbons, sewage and low oxygen concentration were identified as possible causes of shell deformation (Geslin et al., 2000). However, the boundary between morphological variations within the same species and deformed specimens is not very well defined and rather bound to subjective interpretation. Therefore, diversity and abundance changes have been considered as the most reliable environmental indictors because, in general, they tend to decrease in those sample locations where heavy pollutant

concentrations occur (Cearreta et al., 2002; Debenay et al., 2001; Armynot du Chàtelet et al., 2004).

1.4.2 The importance of monitoring programs

The increasing concern for marine ecosystem health has led to a strong demand for suitable monitoring programs, capable of quantitatively assessing the quality of marine habitats and the biotic response to various types of environmental impact. Hence, the major focus of monitoring programs is to obtain baseline data and to detect natural and anthropogenic trends in status and conditions over time (Dauer and Alden, 1995; Overton and Stehman, 1996). The terms "biological indicators" and "biological monitors" have been used in varying ways to describe different approaches and techniques for studying biological responses to pollution (Loeb, 1990). However, the field of biological monitoring can be seen as both qualitative (bio-indicator) and qualitative (bio-monitoring); the former is diagnostic of the health of an aquatic ecosystems, while the latter can be measured. Ecologically, the concept of function space provides the theoretical framework for understanding the importance of biological monitoring to any evaluation of environmental health (Loeb, 1990). The organisms that inhabit aquatic ecosystems are the fundamental sensors that respond to any stress affecting that system. The health of an aquatic ecosystem is reflected in the health of the organisms that inhabit it. Any stress imposed on an aquatic

ecosystem manifests its impact on the biological organisms living within that ecosystem (Loeb, 1990).

Martin and Coughtrey (1982) have provided a particularly useful discussion of the terms "biological indicators" and "biological monitors". They proposed that the two terms are in fact distinct, although many authors have employed them synonymously. Biological indicators (also termed, "bio-indicators') are considered to be organisms which, by their presence or absence, indicate the existence or abundance of a particular critical factor. Thus, all organisms exhibit a defined tolerance to an environmental stimulus (whether the latter is natural or anthropogenic in nature) and can exist in particular locations only within their zone of tolerance. Within this zone of tolerance enhanced exposure to contaminants or to natural stresses (e.g. increasing or decreasing salinities or temperatures) may be met through compensation mechanisms, although signs of toxicity are likely to occur as the upper limit of the zone of tolerance is approached. Through its presence or absence in a particular environment, a biological indicator acts as a signal of the existence of a stimulus at or above a given threshold or critical level (Martin and Coughtrey, 1982).

1.4.3 Foraminifera as a bio-monitoring tool

Several studies on living foraminifera have used these organisms as bio-indicators of intertidal environments (e.g. Murray, 1971; de Rijik, 1995;

Redois and Debenay, 1996; Redois and Debenay, 1999; Debenay et al., 2000; Debenay and Guillou, 2002). Other studies focused on using foraminifera as sedimentary indicators (tidal effects, water movement, settling velocities, sediment transportation), anthropogenic indicators (sewage, heavy metals, petroleum, chemical, pesticides, anoxia, and salinities changes), and global indicators (UVB radiation and sea level changes) (Alve, 1995; Alejo et al, 1999; Brewster-Wingard and Ishman, 1999; Yanko *et. all*., 1999; Hallock, 2000). Ultimately, these studies concluded that the composition of foraminiferal faunas and the presence of morphological abnormalities in foraminiferal tests can be used as indicators of pollution (e.g. Alve, 1991; Yanko et al., 1994, 1999; Alve, 1995; Yanko, 1997; Samir, 2000; Samir and El-Din, 2001).

Foraminifera are preferred as bio-monitors for pollution due to several advantages in comparison to the more commonly used macrofaunal organisms (e.g., Alve, 1995a; Mojtahid et al., 2006; Bouchet et al., 2007; Alve et al., 2009; Jorissen et al., 2009). Advantages for incorporating benthic foraminifera into biomonitoring programs include: (1) their small size and good preservation potential, which facilitates logistics of sampling and experiments (Alve, 1991; Grant et al., 1995; Scott et al., 1995; Bresler and Yanko, 1995; Angel et al., 2000); (2) benthic species are among the most abundant microorganisms found in the surface sediments in shallow and

marginal-marine environments; (3) their sensitivity to changing environmental conditions, thus potentially providing information on the quality of the ecosystem where they live (Schönfeld et al., 2012); (4) their density in marine sediments, between 100 and 1000 living individuals > 63µm per 100 cm^3 surface area (Murray, 2006), is higher than that of macrofauna, which provides a highly reliable database for statistical analysis, even when small volumes of sediments are available; (5) benthic foraminiferal faunas are highly variable; about 20 to 50 species per 300 individuals are to be expected in near-coastal environments; (6) benthic foraminifera also tend to have shorter life cycles, which suggest more rapid responses at the community level but greater temporal variability, and more taxa per site means more effort must be expended on taxonomic identification. The benefit of this additional effort is more data for detecting differences through time among sites (Patrick, 1975).

1.4.4 The FOraminiferal BIoMOnitoring (FOBIMO) initiative.

The use of foraminifera in biological monitoring studies has recently increased and is very likely to increase in the future. But a wide range of very different methods was used for sample preparation, faunal record and data interpretation. Since 2011, several workshops have been organised to standardize the methodologies of using foraminifera as a biomonitoring indicator. This effort directed to the birth of the international FOraminiferal

BIoMOnitoring (FOBIMO) group, a group of scientists developing the use of foraminifera as bio-indicators with the objective of developing a standardised foraminiferal biomonitoring tool and making it available to a wider community. The FOBIMO group combines the efforts of 40 international scientists (Europe, USA and Japan) working on foraminifera as bio-indicators of environmental quality. A standardised sampling protocol was proposed and became officially the standard for foraminiferal research (Schönfeld et al., 2012).

1.5 Aquatic ecosystem.

A healthy ecosystem is composed of biotic communities and abiotic characteristics, which form a self-regulating and self-sustaining unit. The community structure of an aquatic ecosystem is sensitive to, and determined by, the conditions and resources available within a habitat. Conditions include abiotic environmental factors, which vary with time and space (e.g., temperature, salinity, and flow) (Begon et al., 1990), while resources are all things consumed by an organism (e.g., food, light, and space) (Tilman, 1982). If a habitat is characterized by conditions that are within acceptable limits and provides all necessary resources for a given species, that species could potentially occur there (Begon et al., 1990).

In contrast, the health of an ecosystem is diminished when the ecosystems capacity to absorb a stress has been exceeded. When organisms

of an ecosystem are exposed to stress, their resistance to displacement from that ecosystem may be exceeded. A stress on an ecosystem can be categorized into one of three types: (1) physical; (2) chemical; or (3) biological alterations. Physical alterations include changes in water temperature, water flow, substrate/ habitat type, and light availability. Chemical alterations include changes in the loading rates of bio-stimulatory nutrients, oxygen consuming materials, and toxins. Biological alterations include the introduction of exotic species (Alve, 1995).

1.5.1 Environmental impacts of marine aquaculture.

The rapid expansion of aquaculture farming during the past twenty years has provoked a serious warning for their impact on the marine environment (GESAMP, 1990; Wu, 1995). Aquaculture, specifically fish farmings, has a direct impact on the quality state of the ecosystem (QSE). The most obvious direct impact of fish farming activities on bottom sediments is the accumulation of organic matter (OM) (Holmer, 1991; Henderson et al., 1997; Karakassis et al., 1998). Fish farming can affect marine ecosystems through the release of dissolved nutrients that can modify pelagic ecosystem functioning (Alongi et al. 2009). The sedimentation of fish faeces and uneaten feed can also lead to reduced biodiversity on the underlying seafloor (Lee et al. 2006; Hargrave 2010), increased anaerobic microbial metabolism, increased nutrient and methane flux from the

sediment (Gowen and Bradbury 1987; Holmer and Kristensen 1992; Hargrave 2010), and reduced bioturbation (Heilskov et al. 2006). Furthermore, the continuous flow of faeces and uneaten food pellets from fish cages alters the quality and the biochemical composition of sedimentary organic matter and causes transformation of the substrate into an anoxic environment (Holmer et al., 2003; Sutherland et al., 2007).

These heavy loads of particulate organic matter (OM) cause variations in the physical and chemical characteristics of the sediment which will have a strong impact on the structure of the benthic assemblages (Brown et al., 1987; Pocklington et al., 1944). The degree of disturbance of fish farms is often only assessed from changes in benthic community structure (Lee et al. 2006). Furthermore, other studies, (e.g. Burford et. al., 1994) proposed that the benthic fauna may be more seriously affected by fine sedimentary organic matter (SOM) because it alters both the available food and preferred substrate. Such changes may cause a collapse of microbenthic communities (Pearson and Rosenberg, 1978). Ultimately, the increase in the organic matter supply leads to a reduction in benthic diversity, richness, abundance and biomass (Brooks and Mahnken, 2003; Klaoudators et al., 2006; Tomassetti et al., 2009).

1.5.2 Fish farms of Scotland.

In Scotland, fish farming is dominated by salmon production, much of which takes place in the sheltered sea lochs of the west coast and adjacent islands. The water bodies of these fish farms are characteristically deep and frequently host muddy sediments that are, in the UK, classified as the Biodiversity Action Plan (BAP) habitat 'mud in deep water' (OSPAR 2010, Wilding 2011). Salmon farming has a variety of environmental impacts related to the flux of farm-derived organic detritus to the seabed (Wilding et al., 2012). The organic enrichment of the sediments immediately beneath the sea cages has a direct impact on the sediments due to the direct accumulation of the dissolved wastes products from the fish farm (Hargrave et al., 1997; Karakassis et al., 1998; McGhie et al., 2000). In addition, the process of fish farming releases nutrients such as nitrogen (N) and phosphorous (P) from fish feed into the marine environment in a soluble form. Recent estimates indicate that, in coastal areas, the release of nutrients from fish farming contributes between 7% and 10% of the total discharge of nitrogen (N), and phosphorous (P), respectively (Mirto et al., 2012).

1.5.3 The regulatory framework directive.

The marine ecosystem is regulated and monitored through international and national legislation (Holmer et al., 2008). The framework directive aims to reach good ecological status of marine environment. The Guidelines for monitoring the quality status of marine ecosystems (QSE) was first established by the European Community Marine Strategy Framework Directive (MSFD, 2008). The MFSD aims to obtain Good Environmental Status (GES) for Europe's marine waters by 2020. Similarly, The European Water Framework Directive (WFD, 2000) obliges all countries to achieve a good status of all water bodies, including marine waters. In the framework of these directives, the scientific communities were involved in monitoring the status of marine environments, and in particular, in describing the impact of pollutants on living organisms. Because of these far-reaching decisions, a large number of monitoring tools have been developed by selecting sensitive key groups or species and by utilizing biological indicators (Borja et al., 2009).

In Scotland, the Marine Scotland Science (MSS), has a strong program of research investigating the impacts of fish farms and has provided both the Scottish government and the Scottish Environment Protection Agency (SEPA) with advice on applications for fish farm leases and the discharge consents necessary for fish farming development (SEPA, 2005). MSS has

developed the scientific basis on which the location guidelines for the authorization of marine fish farms in Scottish water are based. MSS has developed mathematical models to predict the level of nutrient enhancement in sea lochs arising from fish farming. The results of these models are used to provide advice on the number of fishes that can be farmed at a particular site. Recently, MMS has conducted field surveys to measure the levels of waste in sea lochs which results from fish farms and record any effect on the benthic environment, providing an assessment of the impact of marine aquaculture in Scottish coastal water (SEPA, 2005).

1.6 Objectives of the thesis.

The primary aim of this thesis is to develop an improved, quantitative understanding of the behaviour of benthic foraminiferal species under abnormal conditions or polluted environments, through both field studies and novel methodologies. In particular, the work focused on the response of benthic foraminifera to environmental changes to test the potential of these species as a bio-monitoring tool in the assessment of the environmental impacts linked to marine aquaculture. Maintaining good environmental status plays a significant role in sustaining biodiversity of the benthic environment. Fish farms in Loch Creran, on the west coast of Scotland, were selected as a representative of both the type of aquaculture practice and location of such activity along the Scottish west coast. The study aimed to

assess whether or not fish farms in Loch Creran have a significant impact on benthic communities through their localized pollution (organic matter enrichments) at the sea floor, and, if so, over what distances from the cages themselves.

Mapping the response of benthic communities will help us to develop a novel approach to assessing and monitoring the quality status of the marine environment along the west coast of Scotland. The concentration of organic matter (OM) in the surficial and in the temporal (down-core) sediments were investigated in this study to assess the environmental pollution levels and to determine how natural and anthropogenic factors influence the distribution and ecology of benthic foraminiferal assemblages in Loch Creran, Scotland. For this purpose, samples, from Loch Creran, were collected during a dedicated research cruise and examined to determine the spatial and temporal (down-core) distribution pattern of living benthic foraminiferal assemblages linked to marine aquaculture.

Principally, the objectives of this thesis can be broadly summarized as follows:

1) To document the spatial distribution pattern in modern benthic foraminifera in Loch Creran. Recording how benthic foraminiferal respond of different sources of organic matter (OM)

contamination would provide an understanding of any changes in their bio-diversity, composition and density. In order to address how aquaculture has influenced the environment of Loch Creran, and whether fish farms have affected benthic foraminifera populations and sediment characteristics in the study area, the organic matter (OM) was analysed in surface samples collected from beneath and around eight floating fish cages as a representative of anthropogenic impacts and from a natural source of OM (river influences) input close to the head of the fjord.

2) Detailed benthic foraminiferal assemblage studies were performed in combination with available environmental parameters, i.e. sediment properties, temperature, water depth. The relationship between oxygenation and species diversity was illustrated and its effect on benthic biodiversity was recorded. The organic matter (OM) enrichment data was also investigated in an effort to identify indicators of adaptability to environmental stress.

3) To identify individual foraminifera which were considered to be the most tolerant species to organic matter (OM) contamination as bio- indicators.

4) To explore the temporal (down-core) distribution pattern of benthic foraminifera and investigate the potential of obtaining paleoenvironmental records for Loch Creran, on the west coast of Scotland. For this purpose, five sediment cores were obtained from the main basin of Loch Creran (from beneath and around fish farming cages) to understand how the fish farming process influences the study site and to reconstruct the baseline (pre-impacted) environment.

CHAPTER 2

MATERIALS AND METHODS

CHAPTER 2

MATERIALS AND METHODOLOGIES

2.1 Introduction

This chapter deals with general information about the study area, Loch Creran, on the west coast of Scotland, and the analytical techniques and methods that were used for the study of foraminiferal assemblages and associated sedimentary environments. The aim of these methodologies is to develop a quantitative understanding of the response of benthic foraminifera to the environmental changes linked to organic matter gradients. This will be accomplished by studying their spatial and temporal (down-core) distribution pattern beneath and around fish farming sites and in areas of the sea loch with high inputs of natural organic matter sources (i.e. the River Creran at the head of the loch). The main environmental variables that affect and control the distribution of the foraminiferal communities will be discussed in greater detail in chapters 3, 4 and 5.

2.2 The study area

The study area of this thesis focuses upon Loch Creran, on the west coast of Scotland (Figure 2.1). The description of Loch Creran is taken from Edwards and Sharples (1986). Loch Creran is a fjordic sea loch- "a semi-enclosed body of water which has a free connection to the open sea and

within which seawater is measurably diluted with fresh water derived from land drainage" (Cameron & Pritchard, 1963). The loch is 12.8 km long and with a surface area of 13.5 km² (Edwards and Sharples, 1986). Sills are a distinguishing feature of the bathymetry, and Loch Creran has two main rock sills, one at the entrance area to the Linn of Lorn and the second separating the main from the upper loch (Figure 2.2). River Creran at the head of the loch, a location where the River Creran ends and Loch Creran begins, is the main source of freshwater input into the loch. River Creran enters at the head of the loch into the upper basin which has a very shallow sill with a mean water depth of 7.5 m and provides a potentially large source of fresh water (and organic matter) inputs that affects the surface waters of loch for its entire length. In general, the maximum water depth in the loch is 49 meters. There is a relatively high input of freshwater into the loch from the River Creran, which flows approximately 4 km upstream from the head of the Loch Creran. The mean freshwater input is 286×10^6 m^3 yr^{-1} and the flushing time is three days (Edwards and Sharples, 1986).

Loch Creran is unique and an important area of environmental scientific interest, due to the presence of extensive reef structures: is it also hosts a number of aquaculture activities, notably salmon farming. These fish farm sites are operated by Scottish Sea Farms Ltd (Equitable House, London) and are considered likely to represent equilibrium conditions in terms of

impact status (see Wilding et al., 2012). The farms are operated by an automated compressed air feeding system (Wilding et al., 2012). Two salmon farming sites have been consented in Loch Creran, each of 1,500t maximum biomass, however, only one site is occupied at a given time. This rotation scheme means that each site is required to lie fallow for two years after use allowing recovery of the benthic environment (Tett P, 2008).

2.3 Sample collection – cruise and fieldworks

The procedures for the sediment sampling are given in this section. Sediment cores were collected from various locations along transects of Loch Creran. There were 10 sampling stations in the main basin during the May 2016 cruise using the research vessel "*Seol Mara*" (SM16) and three sampling locations in the upper basin (River Creran) during the May 2018 *Morwena* cruise (MW18) (Figure 2.3). The sampling locations were chosen to analyse the impacts of fish farming on foraminiferal community composition. In addition, a range of sediment samples were collected from the upper basin to reflect transition from samples dominated by riverine input (close to the mouth of the River Creran) to stations dominated by marine input (fish farms). The thesis employs two sampling strategies which aims to capture the distribution and the diversity of benthic foraminifera across the study area. The first focuses on sampling the surface sediments to study the spatial distribution pattern of foraminifera in relation to organic matter

gradients. For the surface sampling, the top (0-1 cm) layer of sediment was split and collected from each core and placed in plastic containers for foraminiferal analysis. The second sampling approach examines the temporal (down-core) dynamics of benthic foraminifera at fish farming environments to reconstruct the palaeoenvironment (pre- and post-impacted environment) through an investigation of relative and absolute abundances of specimens. The foraminiferal sampling was carried out in this study following of the FOraminiferal BIoMOnitoring group (FOBIMO) recommendations as much as possible, in order to test the practicability of the guidelines (Schönfeld, 2011). The two (i.e. spatial and temporal) taxonomic investigations conducted in this study employ relatively similar materials and methods, which are outlined below.

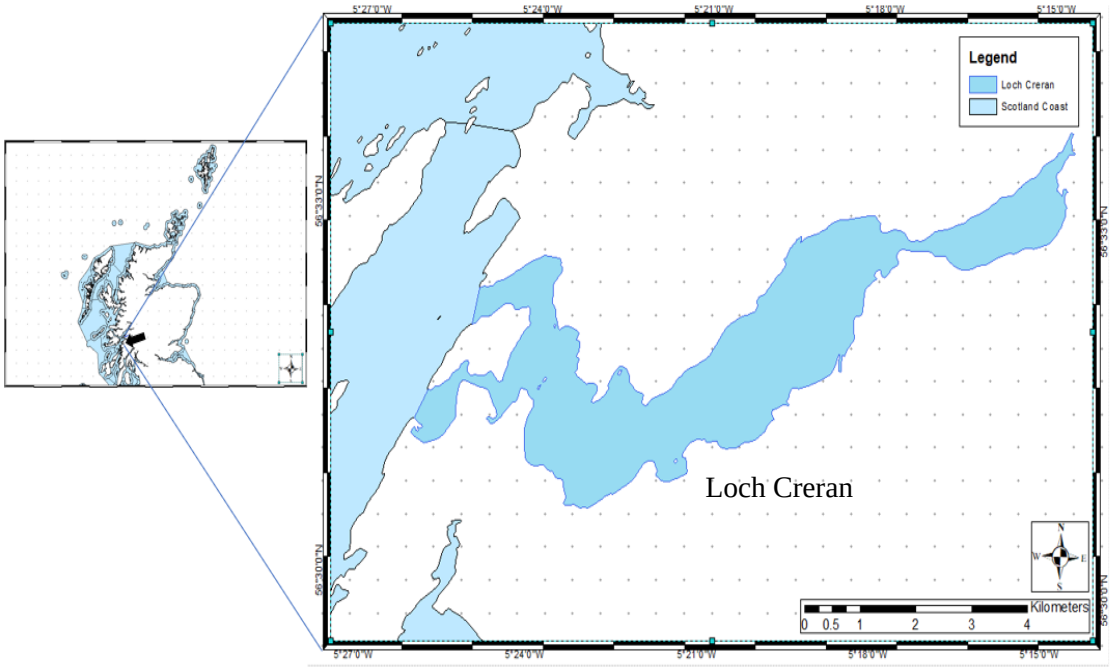

Figure 2. 1 Location of Loch Creran, on the west coast of Scotland

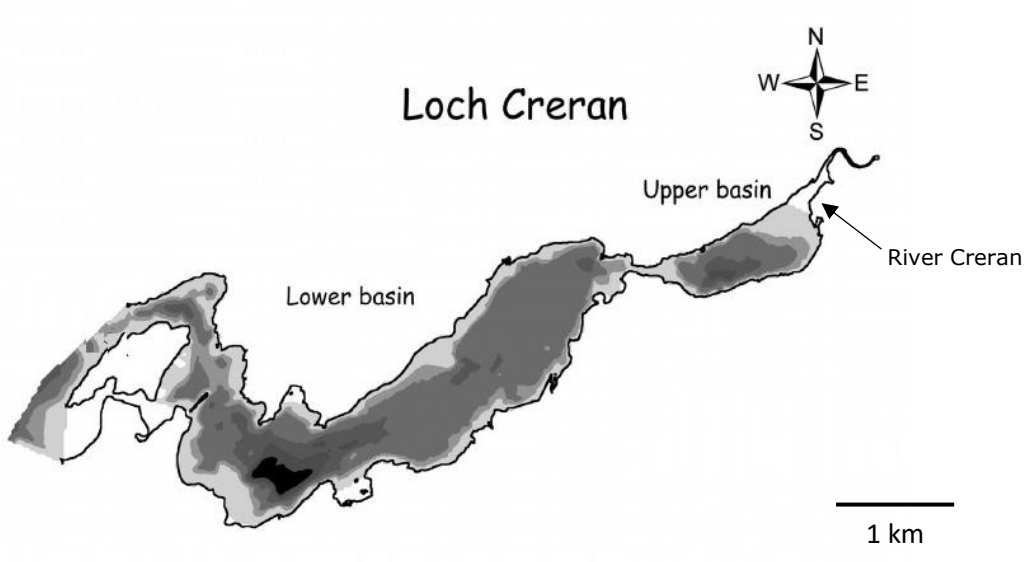

Figure 2. 2 Loch Creran bathymetric map showing the two basins, darker shading represents deeper water at 10m depth intervals.

2.3.1 Surface sediment samples

Twenty surface sediment samples were collected, across the lower (main) and the upper basin of Loch Creran for benthic foraminifer and sedimentological analysis and in representative localities along gradients that were intended to reflect the impact from organic matter supply or as un-polluted stations (away from the farming sites) (see figure 2.3). In order to study the spatial distribution variation of foraminiferal assemblages and to assess the response of these species to the environmental impact linked to organic matter gradient, the stations were chosen to provide a range of sediment samples to reflect transition from samples dominated by riverine input (close to the mouth of the River Creran) to stations dominated by marine input (fish farms). Hence, stations were carefully selected to be sampled directly beneath the polluted sites (fish farming cages), at increasing distance from the cages and from the Creran Head.

Fish farms are known to cause localized pollution on the sea floor with daily output of varying quantities and qualities of organic matter. This has a significant impact on the morphology, behaviour and biodiversity of benthic communities below fish farm sites. In addition, excess supply of organic material can lead to a collapse of the benthic community. (e.g., Pearson and Rosenberg, 1978). To test the impact of the fish farming aquaculture on the life of the benthic foraminiferal community, we collected sediment samples

close to the cages and from areas far away from the farming sites (controlee sites) to ascertain whether or not there were significant faunal differences between all these sampling locations. All oceanographic positions of the cruises were obtained using Global Positioning Systems (GPS) (Figure 2.3). Sampling dates and the coordinates with devices used to collect the samples are listed (Table 2.1) and plotted (Figure 2.3).

The samples were obtained using two devices, the Craib corer (CC) (Craib, 1965) and the Sholkovitch corer (SC) (used on the May 2016 *Seol Mara* cruise). In addition, a direct surface sample from the top layer of the sediments (0-1 cm) in the upper basin were collected using a Van Veen grab sampler (GB) (during the May 2018 *Morwena* cruise). The Craib corer (CC) enables the sediment water interface to be sampled in most fine-grained sediments. The corer was lowered to the sediment surface in order to obtain sediment cores with undisturbed water-sediment interface layer. In each location, triplicate of sediment cores was obtained; the corer was lowered three times in order to obtain three separate sediment cores. This procedure would be repeated if the sediment cores obtained were found to be disturbed. The Sholkovitch coring (SC) device was used to obtain core samples of up to 50 cm in length which were used for the down-core foraminiferal analyses (Chapter 5).

For surface analyses, the upper-most centimetre (0 _ 1 cm) of the undisturbed seabed sediment for each core was sampled as an extruded slice and then used to determine foraminiferal content, see figure 2.4. These samples were stored in buffered ethanol stained with Rose Bengal (2 g of Rose Bengal in 1000 ml alcohol) to avoid protoplasm degradation and to distinguish living (stained) from dead (unstained) specimens (Murray and Bowser, 2000). Each sample was labelled with a unique ID code including an abbreviation of the device used, station and the core section (see Table 2.1). Seventeen surface samples from the main basin were assigned the spatial foraminiferal distribution analysis. Three of them, SC-02, SC-03, and SC-06 were directly beneath the fish farming cages (polluted stations), while the others were collected either at a control site or further away from the fish farms. Three surface samples were collected from the upper basin samples and were labeled as follow; GB-03-C, GB-07-A, GB-09-A. Another sub-sample from each core was taken from a depth of 1 – 2 cm and the sediment were archived in refrigerated (4° C) or frozen (-20° C) conditions to be used for grain size, elemental analysis, C/N and loss-on-ignition analyses (Chapter 3).

At station 03, after several attempts at coring, we succeeded in collecting the bottom sediments and collected three Craib cores (CC). From this point of the field cruise (i.e. station 4 and onwards) and for further

sampling of the impacted fish farm site, we switched to sampling with the Sholkovitch Corer (SC). As mentioned above, the Sholkovitch allow us to collect large volumes of sediment.

Three replicate cores were collected for foraminiferal assemblage analysis. Sampling three replicate cores was applied to follow the protocol of FOBIMO for sampling procedure (Schönfeld al. et., 2012). In environmental studies, replicate sampling aims to minimize the problem of misclassification in distribution patterns of benthic foraminifera. Depending on FOBIMO protocol, the use of replicates has been considered to be as a common methodology in benthic foraminiferal studies. Considering replicate samples in the methodology will lower the risk of misleading assessment of the ecology status rather than if their data were based on only one sample /station. The replicate samples should follow the same distribution pattern which should increase the degree of confidence that the achieved results are reliable and correct (Schὸnfeld al. et., 2012).

Table 2. 1 Surface sample Id codes in relation to their sampling locations, date and time of collection, water depth and device used to obtain the samples.

Sample ID Code	Device	Latitude, N	Longitude, W	Date [UTC]	Time [UTC]	Depth [m]
CC-01-A	Craib corer	56° 31.141	5° 22.386	30.05.2016	10:23	37
CC-01-B	Craib corer	56° 31.134	5° 22.299	30.05.2016	10:30	37
CC-01-C	Craib corer	56° 31.133	5° 22.298	30.05.2016	10:40	38
CC-02-A	Craib corer	56° 31.372	5° 21.434	30.05.2016	10:53	29.9
CC-02-B	Craib corer	56° 31.372	5° 21.437	30.05.2016	11:45	30
SC-02-A	Sholkovitz	56° 31.373	5° 21.436	30.05.2016	12:23	27.2
SC-03-A	Sholkovitz	56° 31.377	5° 21.466	30.05.2016	1:41	29.1
CC-03-A	Craib corer	56° 31.376	5° 21.465	30.05.2016	1:49	29.2
CC-03-B	Craib corer	56° 31.375	5° 21.464	30.05.2016	1:58	29
SC-04-A	Sholkovitz	56° 31. 368	5° 21. 475	30.05.2016	2:24	29.8
SC-04-B	Sholkovitz	56° 31.370	5° 21.478	30.05.2016	2:30	29.7
SC-05-A	Sholkovitz	56° 31. 359	5° 21. 565	30.05.2016	2:44	30.1
SC-06-A	Sholkovitz	56° 31.486	5° 21.167	30.05.2016	2:54	27.4
SC-07-A	Sholkovitz	56° 31.483	5° 21.147	30.05.2016	3:06	24.8
SC-08-A	Sholkovitz	56° 31.520	5° 21.065	30.05.2016	3:16	23
GB-03-C	Van Veen Grap	56° 33.188	5° 15.130	22.05.2018	11:33	12.5
GB-07-A	Van Veen Grap	56° 33.010	5° 15.072	22.05.2018	12:09	13.7
GB-09-A	Van Veen Grap	56° 32.937	5° 15.549	22.05.2018	12:18	22.7
GB-20-A	Van Veen Grab	56° 31.430	5° 20.220	22.05.2018	14:29	17.5
GB-28-A	Van Veen Grab	56° 31.293	5° 22.694	22.05.2018	15:23	29.6

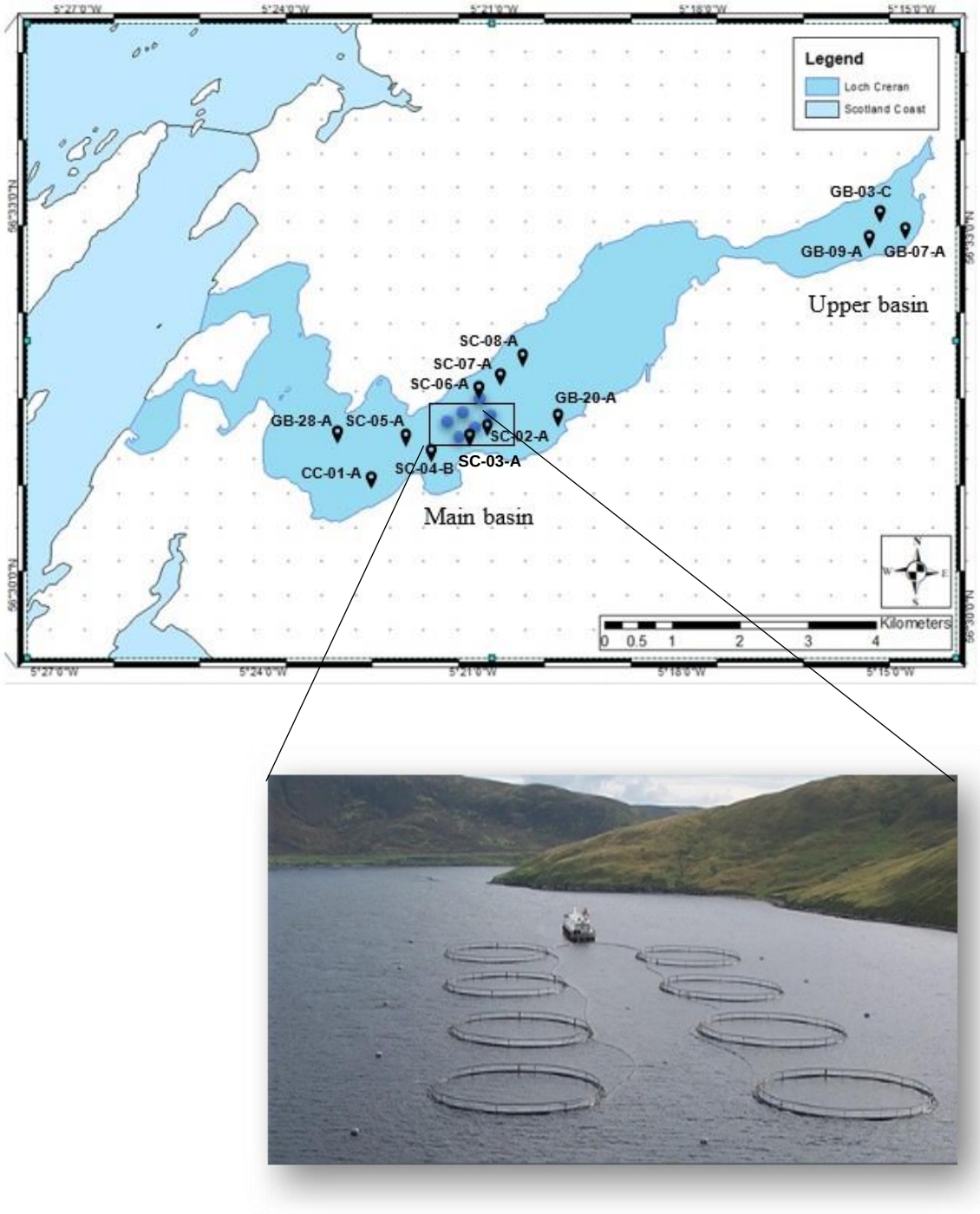

Figure 2. 3 Map showing the sampling locations in Loch Creran, at which benthic foraminifera were collected for studies included in the present thesis, inset photograph showing the arrangement of fish cages.

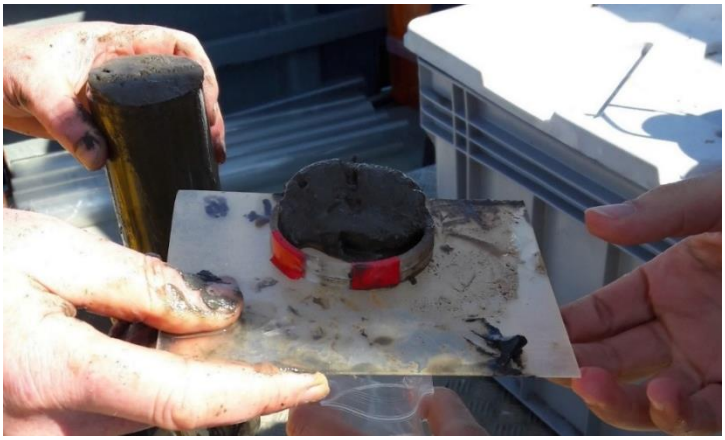

Figure 2. 4 The top centimetre (0_1 cm) slice of the undisturbed sediment from each core was sub-sampled to provide material for foraminiferal analysis.

2.3.2 Down-core sediment sampling

The sediment samples used for the temporal (down-core) foraminiferal analyses (reported in Chapter 5) were collected from fish farming and non-fish farming sites along transect in Loch Creran. Sample stations for the vertical distribution study are provided in Figure 2.5. The Sholkovitch coring device (SC) was the only instrument used at this point to obtain cores (up to 40 cm in length) for foraminiferal and geochemical analysis. The Sholkovitch cores were sliced at 1cm intervals whilst on board (during the *Seol Mara* 2016 cruise). The down-core foraminiferal analyses were carried out in two cores. The cores were labelled as follows: the fish farming site (i.e. the impacted) (SC-02-A) and the non- fish farming site (i.e. from a station at the furthest point from the farming cages) (SC-04-B) (Figure 2.5). For the fish farming core (SC-02-A), a 14-cm sediment core was collected for this station using the Sholkovitch corer, whilst for the non-fish farming core (SC-04-B), 11-cm core sediment was sampled and processed for foraminiferal analysis. Three replicate cores were obtained for SC-02-A (the suspected impacted sites close to the fish cages). Immediately after recovery, the sediment cores were longitudinally split in equal volumes, subsampling at 1 cm thick intervals every 1 cm. Each sub-sample was placed in a plastic bag that was identified with a specific sample ID code and was subsequently stored in a freezer (- 20° C) until they were processed.

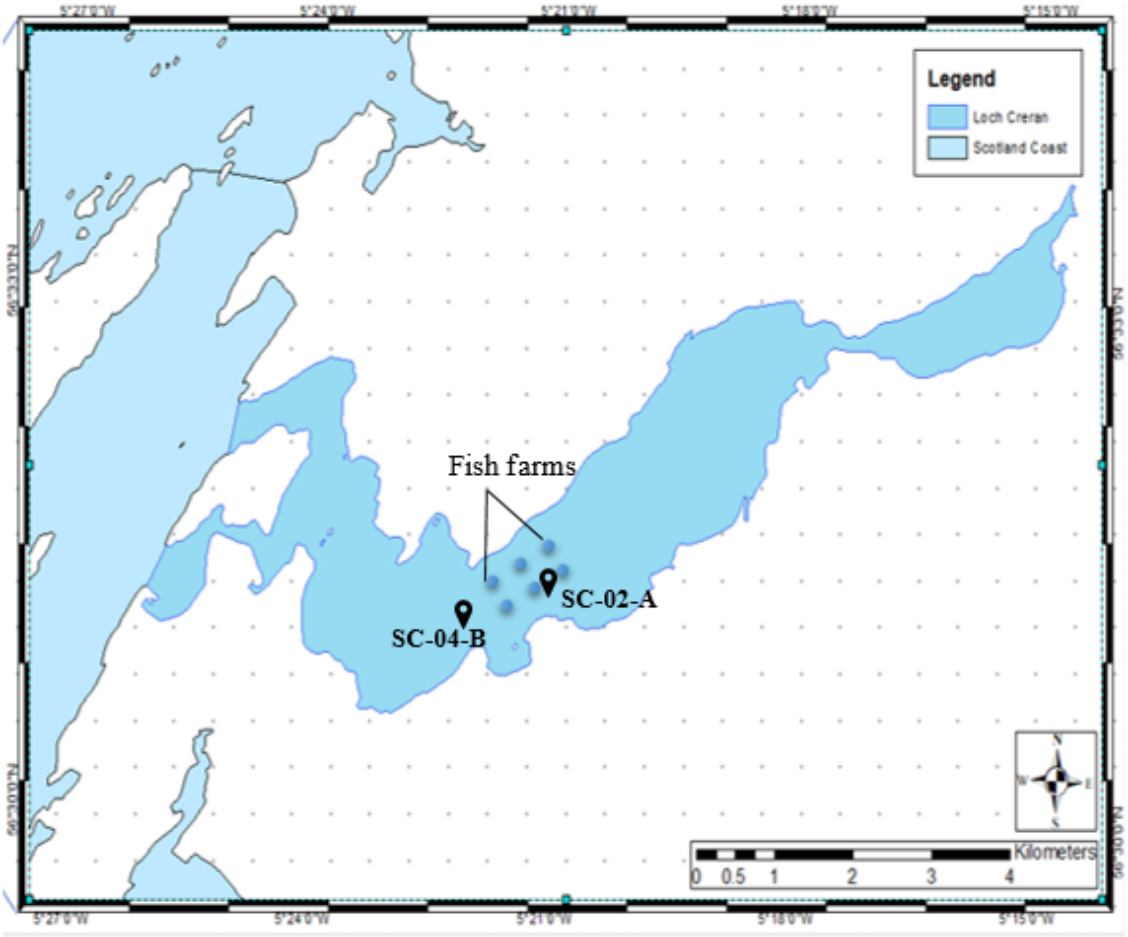

Figure 2. 5 Map showing the sampling stations (black dots) for the temporal (down-core) foraminiferal analysis (see table 2.1 for location details); approximate fish cage locations are indicated (blue dots).

2.4 Sample preparation for foraminiferal analysis

The sample preparation for foraminiferal analysis consists of relatively simple techniques, essentially relying on sieving the sediment samples to concentrate the foraminifera before counting. The observation, sorting and counting of foraminifera were performed mainly on dried samples at relatively low magnification (x35). For the preparation of the surface samples, and in order to study foraminiferal populations, the samples were preserved in Rose Bengal-stain, a stain used to differentiate between living and non-living foraminifera following the methods of Walker et al., (1974) and Walton (1952). This procedure is used to avoid protoplasm degradation and to distinguish living (stained) from dead (unstained) specimens (Murray and Bowser, 2000). The stain was added to the sediments as soon as they had been sampled to selectively stain the living cells. The sample containers were well sealed. The foraminifera living at the time of sampling should retain the pigmentation during the picking stage of the process.

2.4.1 Foraminifera processing

In the laboratory, from each sample the stained sediment was sieved through two sizes of mesh sieves: a 125 µm and a 63 µm sieve. Foraminifera settled in the two sieves since their size ranges within both these size fractions (Murray, 2006). Samples were sieved until the outflowing water

ran clear (i.e. no fine clays or fine sediment particles present). Several rinses were required to clean up all foraminiferal individuals, proceeding with a final rinse with distilled water. The sieves were thoroughly washed in between samples and submerged in methyl blue solution, which stains calcium carbonate blue thus allowing identifying any residual contaminant specimens within the sample. The sediment samples were poured in a labelled glass beaker and left in the oven (at 40 ^{o}C) until completely dry (Murray, 1991a). The dried samples were then transferred to small labelled bottles with a specific identification number for later microscopic examination.

2.4.2 Foraminifera picking

A total weight for each sieved sample was determined and the 63_125µm and 125 µm fractions (or residues) were obtained (from the sieving methods) for use in foraminiferal picking and analysis. Picking and separation of foraminiferal specimens were done manually from the >125µm fraction. A stereomicroscope (x35 magnification) was used to pick and identify the foraminifera. Concerning benthic foraminiferal counting, the extraction of all specimens present in the whole sample is often necessary for a statistically representative sample for a population analysis. However, the number of individuals in the sample may still be too high to achieve systematic counting. When the density or the concentration of microfossils

is high, observation and counting on the plate cannot be realistically performed on the whole sample. We then proceed to extract individuals from a representative fraction of the sample with the help of a microsplitter that can separate the sample into two equal halves. The sample can be split into as many fractions as necessary (x2, x4, x8, x16, x32...), depending on sample abundance, to obtain a fraction containing a population with a reasonable density for analysis. It is important to record the final fraction of the sample (1/2, 1/4, 1/8, 1/16, 1/32...), represented by the sample, in order to calculate the overall concentration. In this study, based on typical sample size and foraminiferal abundance, the weight fraction was adopted to equal to 1/8 of the sample to yield reliable counting from which a sufficient number of specimens could be obtained.

2.4.3 Counting and observation

The splits residues were evenly distributed across a black gridded picking tray for observation under the stereo microscope. The picking tray is divided into equal size squares. The foraminifera can be manipulated with a fine moist artists brush to avoid static. Where possible, at least 200-300 individuals were picked (Murray, 2006) to achieve a target number of specimens needed for a reliable estimation of foraminiferal abundance; typically, 300 specimens (Patterson and Fishbein, 1989). This provides a 99% confidence interval that species making up >5% of the assemblages are

captured (Fatela and Taborda, 2002). Specimens were picked from each square of the entire split, or from random squares (to avoid biasing towards a certain size of specimen) if the number of foraminifera in a sub-sample split were particularly high. Every specimen within a square was picked before moving onto the next square to avoid biasing results towards larger, more visible individuals. Individuals were then sorted by species on a gridded microscope slide, counted and catalogued in a spreadsheet. Their identification often requires the observation of both sides (e.g. dorsal and ventral) which can be viewed in detail under Scanning Electron Microscope (SEM) at a later stage. Benthic foraminifera in this study were identified to species level following the classification of Loeblich and Tappan (1988) (see chapter 4).

2.5 Foraminiferal analysis

The foraminiferal analysis was conducted on the total assemblages (living and dead). For the study of benthic foraminiferal assemblages, the identified species were counted to obtain quantitative statistical data to help us draw distribution maps of the individuals and to yield a descriptive understanding of the diversity of species in the studied area. Sediment replicates were considered in this study (according to the methodology indicated by (Schönfeld. al. et., 2012). The data collected in this study have been analysed statistically to underpin the interpretation of the faunal data

and to support any environmental reconstructions. The community composition statistics were derived following Murray (1973, 1991), including total abundance, richness, as well as various diversity measures.

Several diversity measures can be used to attempt offsetting the bias resulting from counting a different number of individuals for each sample. Ideally, we would count the same number of specimens (300), and then a direct comparison of species diversity could be made from the raw data. However, when a sample is prepared it is necessary to pick out all of the specimens in the fraction of sediment used, in order to eliminate error in selectively choosing which specimens to pick. Hayek and Buzas (1997) describe a variety of diversity indices used to obtain diversity measures in natural populations, and recommend Fisher's alpha for its ease of calculation, and results being as reliable as any other method and this is compared with other diversity measures (e.g. Shannon index). The measures of diversity were calculated using PAST v.2.17 (Hammer et al., 2001). The diversity indices for benthic foraminifera were determined by calculating the Fisher alpha (α) species diversity (Fisher et al. 1943) and the Shannon-Weaver index (H) to identify changes in species diversity. The Fisher Alpha measure of species richness was calculated for each station in the study area. Based on Fisher et al. (1943), this score reflects biodiversity based on the number of individuals and species recorded from a sample. Values of α

(diversity) can be determined from a base graph by plotting the number of species against the number of individuals in a sample (Murray, 1991: 319). When determine the diversity of samples, and for accuracy, the number of individuals in this study was recorded and the total specimens were counted up to 300 for all surface samples. The diversities were calculated using the statistical computer package PAST (Hammer et al., 2001).

Relative abundance is defined as the percentage of each foraminiferal species in relation to all other counted foraminiferal specimen in a sample and is calculated by dividing the total number of individuals. Absolute abundance is calculated by dividing the number of foraminifera picked from each sample by the fraction picked, and then dividing by the number of grams originally sampled (around 100 g for each sample) to obtain a standard concentration, expressed as specimen per gram. Dried sample weights were the only data given, and so 'specimens per gram' refers to dried weight only (> 125 μm fraction). More detailed discussions of these statistical techniques used in this thesis are provided in relevant chapters to give an understanding of the data processing method. All analyses in this study were computed using the software of Hammer et al. (2005).

2.6 Environmental variables

In this study, the environmental variables were considered prior to foraminiferal analysis including bottom water temperature (BWT), water

depth, the dissolved oxygen (DO_2) concentration and the organic matter (%OM) contents. A full account of the environmental variables and methods of analysis are provided in chapter 3.

2.7 Taxonomy of benthic foraminifera

Foraminiferal species were identified according to the classification scheme of Loeblich and Tappan (1988). Care has been taken to ensure each individual specimen matches the morphology (as some genera exhibit significant variation) of a regional identification of benthic foraminifera (Austin, 1991). For curation purposes, individuals were placed onto a taxonomic slide with a black background and white numbered grid pattern. Samples were counted in an attempt to achieve ≥300 individuals or more (Fatela and Taborda 2002), although this was not always possible. A discussion of foraminiferal taxonomy is outlined in chapter 4.

2.8 Scanning Electron Microscope (SEM)

Finally, in order to achieve a reliable identification (and record) of the benthic foraminifera present, Scanning Electron Microscope (SEM) images were obtained at the Electron Microscope Unit, University of St Andrews. Prior to imaging, foraminiferal individuals were mounted onto SEM stubs covered with double-sided adhesive tabs and gold-coated. The photographs were of insufficient quality to be published, but provided useful guides for species identification (see chapter 4).

CHAPTER 3

ENVIRONMENTAL VARIABLES IN THE STUDY AREA

CHAPTER 3

ENVIRONMENTAL VARIABLES IN THE STUDY AREA

3.1 Introduction

Benthic foraminiferal communities exhibit sensitive indicators and readily observable changes in response to any modification in the marine environment (Pearson & Rosenberg, 1978). In order to measure and examine changes in the structure of benthic communities, sedimentological and biogeochemical characteristics of the sediments were identified. Many authors have suggested that the main environmental parameters controlling the foraminiferal distribution are dissolved oxygen and food (e.g. Gooday 1986; Corliss and Chen 1988; Mackensen and Douglas 1989; Corliss and Emerson 1990; Barmawidjaja et al. 1992; Jorissen et al. 1992; Rosoff and Corliss 1992; Rathburn and Corliss 1994; Jorissen et al. 1995). Hence, in this study, the dissolved oxygen (DO_2) in bottom water, the amount of organic matter (OM) content in the sediment and sediment grain size were measured as representative environmental parameters to indicate the ecological conditions of the benthic environment. All of these parameters may influence the distribution of benthic foraminifera (Murray, 1973; Alejoet al. et., 1999).

The OC content in sediments, both natural and anthropogenic, is often considered to be one of the major factors affecting the health of benthic ecosystems (Cocito et al., 1990). It is generally becoming one of the most common forms of disturbance in the benthos (Weston, 1990; Gee et al., 1985). The major objective of studying these parameters is to assess the impact of organic loading from fish farms waste on the benthic environment beneath and surrounding the fish cages, and the OC accumulation in fjord sediments in the upper basin of Loch Creran (river influenced) in order to investigate how foraminiferal spatial distribution changes in respond to these organic matter enrichments. For foraminiferal analysis, the following biotic descriptors: total density, richness, abundance of dominant taxon and abundance of tolerant taxa will be investigated and discussed in chapter 4.

3.2 Dissolved oxygen (DO_2) and bottom water temperature (BWT).

The bottom water temperature (BWT) and the water dissolved oxygen (DO_2) readings were measured at the SAMS laboratory (the Scottish Association for Marine Science) immediately after collection using PH indicator system and the readings were determined for each sample station. In this study, eight bottom water samples (representing stations 01 to 08), which were collected during the May 2016 cruise, were analysed in order to provide the relevant measurements for these two parameters. The maximum average

bottom water temperature (12.6°C) was recorded at station 01(represented by the samples CC-01-A, CC-01-B and CC-01-C), whilst station 08 (represented by the sample SC-08-A) has the minimum recorded temperature (10.8°C). In general, there was no significant variation in average temperature observed in the study area. Table 3.1 and Figure 3.2 illustrates the average bottom water temperature values in relation to their water depths at the study area.

While BWT and water depth were of minimal importance to the distribution of benthic foraminifera, the concentration of bottom water dissolved oxygen (DO_2) was a good environmental parameter which usually reflect the quality status of the benthic environment. Bottom water dissolved oxygen is considered to be a fundamental requirement for the maintenance of balanced populations of living marine organisms. The bottom water from just above the sediment-water interface of the surface samples was immediately transferred to separated containers, sealed, and kept in dark and cold boxes (-7° C) for subsequent bottom water dissolved oxygen analyses.

Table 3. 1 The average bottom water temperature (BWT) readings recorded from the study area, Loch Creran (May 2016).

Stations	*Sample code id*	*Average Temp C°*	*water depth (m)*
Station 01	CC-01-A	12.6	*37.*
Station 02	CC-02-A	12.0	*29.9*
Station 03	SC-03-A	11.7	*29.1*
Station 04	SC-04-B	11.2	*29.8*
Station 05	SC-05-A	11.9	*30.1*
Station 06	SC-06-A	12.1	*27.4*
Station 07	SC-07-A	11.4	24.8
Station 08	SC-08-A	10.8	23
Station 09	GB-03-C	-	12.5
Station 10	GB-07-A	-	13.7
Station 11	GB-09-A	-	22.7
Station 12	GB-20-A	-	17.5
Station 13	GB-28-A	-	29.6

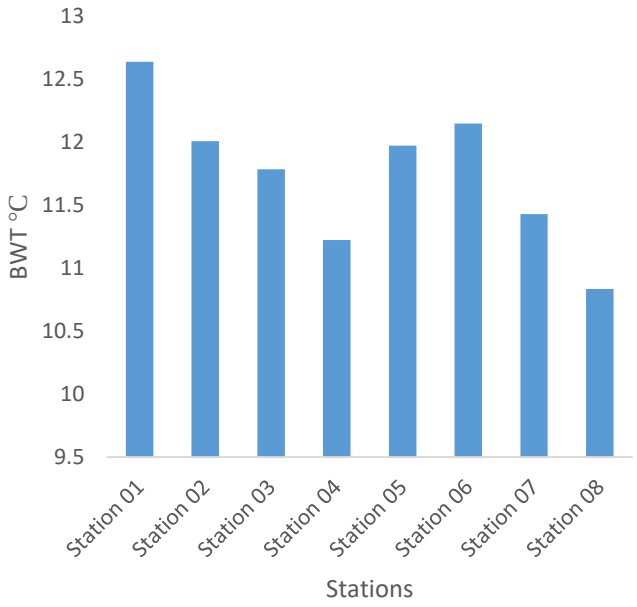

Figure 3. 1 Average bottom water temperature (BWT) readings at each sampling station, Loch Creran (May 2016).

3.2.1 Results

The analytical results of the bottom water DO_2, Table 3.2 and Figure 3.2, show a clear reduction of the concentration of DO_2 beneath fish-farming sites; stations 02, 03, and 06. In general, when DO_2 decrease in concentration, this creates a stressful and harsh environment, in which only organisms adapted to the oxygen-depleted conditions can survive (Moodley et al. 1997). However, it was observed that the DO_2 was also low in station 08 (away from farming sites) which characterised by a relatively high foraminiferal density. One possible explanation to this finding could be linked to the difficulty to maintain a stable water concentration during field work. Overall, the general result suggests that DO_2 can be considered as a factor with a clear effect on the distribution patter of benthic foraminiferal species (Chapter 4).

Table 3. 2 The average of bottom water DO_2 data, BWT C° and water depths for all the stations.

Stations	*Average DO_2 /mg/L*	*Average (BWT) Temp C°*	*Water Depth*
Station 01	262.4	12.6	37.0
Station 02	256.3	12	29.9
Station 03	251.8	11.7	29.1
Station 04	259.2	11.2	29.8
Station 05	258.9	11.9	30.1
Station 06	253.2	12	27.4
Station 07	253.7	11.4	24.8
Station 08	251.3	11.8	23.0

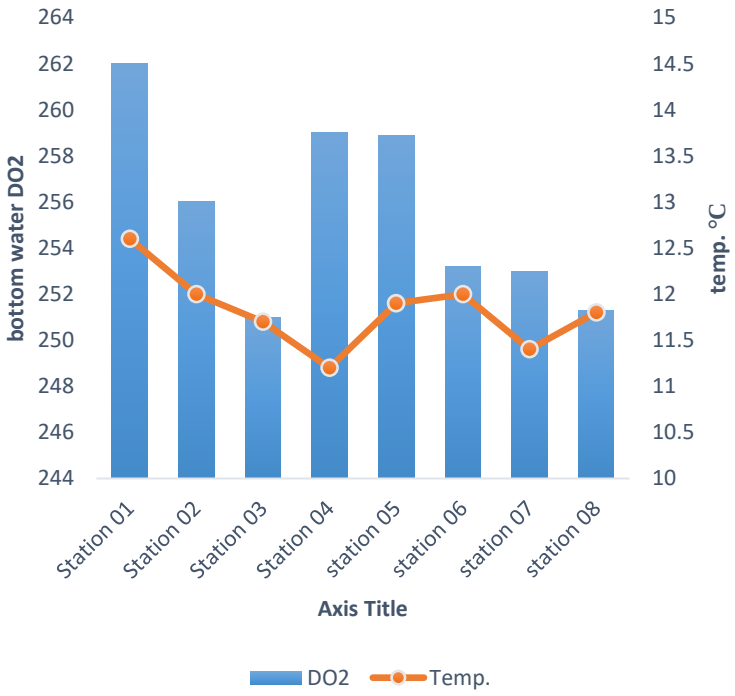

Figure 3. 2 The analytical results showed a clear reduction of the concentration of the bottom water DO_2 beneath fish-farming cages (see figure 2.3).

3.3 Grain size analysis

Sediment grain size is an important parameter controlling benthic foraminiferal distribution in marine environments (e.g., Basso and Spezzaferri, 2000, Celia Magno et al., 2012). The grain size distribution in this study was measured in combination with other factors related to it, such as organic content and water dissolved oxygen (DO2) concentration (e.g., Jorissen, 1987). The objectives of the grain-size analyses were to accurately measure individual particle sizes, to determine their frequency distribution, and to calculate a statistical description that adequately characterizes the sample. The techniques and equipment used for particle-size analysis were carried out using the Coulter LS230 instrument Particle Size analyses (PSA) at the University of St Andrews, using untreated samples. In order to obtain the particle size distribution, approximately 10g of sediment was sub-sampled and weighted from the surface sediment and core samples. Three repeated runs were carried out on each sample. The LS230 software generated statistical analyses for the mode, median and mean of the measurements and these data were exported into an Excel spreadsheet.

3.3.1 Grain size analysis for the surface samples

Sediment grain size analytical results from Loch Creran are summarized in Table 3.3 and Figure 3.3. The results show that the studied sites are mostly located within silty to sandy-silt sediment. In some areas, the sediment has a high fine fraction content, which may reach values up to about 90%. The silt-rich sediments dominated the upper basin (close to the River Creran). High percentages of the silt were recorded in samples GB-03-C, GB-07-A and GB-09-A, with 86.45, 86.05 and 86.99 %, respectively. The grain size distribution of the main basin sediments of Loch Creran, where mostly silty, except in two stations where sand is slightly predominant (e.g. Stations 03 and 04).

3.3.2 Grain size analysis for the down-core samples

The down-core grain size analysis was performed on the cores which were matched specifically to samples of foraminiferal analysis. This includes cores at stations 02, 03, and 06 which represents the sites closest to the fish farms and stations 04 and 08 which were located further away from farming sites. Table 3.4 lists the grain size analysis data for the down-core samples. Generally, fine silt is dominant at all depths of the cores.

Table 3. 3 Surface Sediment samples grain size analysis at Loch Creran.

Stations	*Sample ID code*	*Latitude, N*	*Longitude, W*	*Depth [m]*	*% Clay*	*% Silt*	*% Sand*	*Mean/Median ratio*	*Skewness*	*Kurtosis*
Station 01	CC-01-A	56° 31.141	5° 22.386	37.00	20.70	46.40	32.8	1.56	4.52	29.61
	CC-01-B	56° 31.134	5° 22.299	37.00	20.00	44.70	35.00	2.05	3.61	14.62
	CC-01-C	56° 31.133	5° 22.298	38.00	19.00	43.10	37.70	1.57	2.55	7.963
Station 02	CC-02-A	56° 31.372	5° 21.434	27.20	18.40	45.00	36.50	1.84	3.14	12.50
	CC-02-B	56° 31.372	5° 21.437	29.90	17.60	43.50	38.70	1.92	2.87	10.15
	SC-02-A	56° 31.373	5° 21.436	30.00	16.50	44.60	38.80	1.55	2.60	9.26
Station 03	SC-03-A	56° 31.377	5° 21.466	29.20	13.00	42.00	44.90	1.57	3.91	20.32
	CC-03-A	56° 31.376	5° 21.465	29.00	13.60	41.60	44.80	1.90	3.08	10.99
	CC-03-B	56° 31.375	5° 21.464	29.00	13.70	42.30	43.80	1.66	3.31	14.43
Station 04	SC-04-A	56° 31.368	5° 21.475	29.80	14.30	42.60	42.80	1.50	2.81	9.62
	SC-04-B	56° 31.370	5° 21.478	29.70	14.50	42.70	42.80	1.54	3.98	23.26
Station 05	SC-05-A	56° 31.359	5° 21.565	30.10	19.20	49.50	31.20	1.49	3.01	11.33
Station 06	SC-06-A	56° 31.486	5° 21.167	27.40	15.10	47.00	37.70	1.88	4.46	25.20
Station 07	SC-07-A	56° 31.483	5° 21.147	24.80	16.90	52.90	30.10	1.47	2.94	10.54
Station 08	SC-08-A	56° 31.520	5° 21.065	23.00	16.10	57.70	26.10	1.43	3.55	16.35
Station 09	GB-03-C	56° 33.188	5° 15.130	12.50	7.35	86.45	6.18	1.55	2.89	10.59
Station 10	GB-07-A	56° 33.010	5° 15.072	13.72	7.55	86.05	6.38	1.59	1.58	2.31
Station 11	GB-09-A	56° 32.937	5° 15.549	22.70	8.84	86.99	4.17	1.64	2.12	5.13
Station 12	GB-20-A	56° 31.430	5° 20.220	17.60	8.32	52.08	19.60	2.05	4.88	31.69
Station 13	GB-28-A	56° 31.293	5° 22.694	29.60	6.22	48.71	45.07	1.30	2.17	8.36

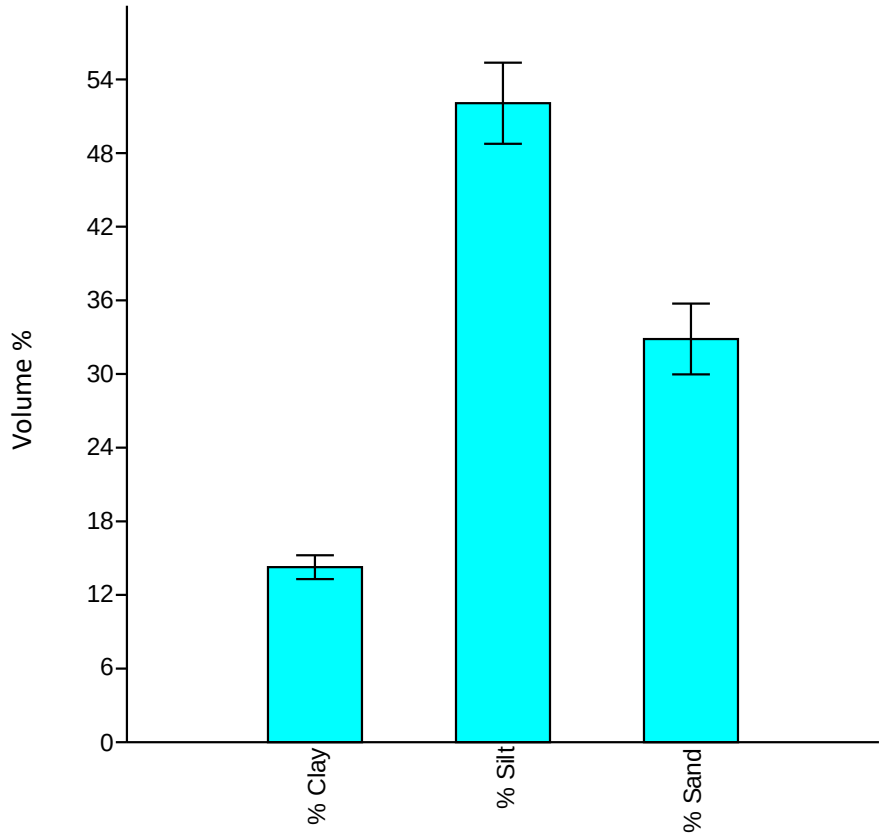

Figure 3. 3 Clay, silt and sand percentages – for the surface sediment samples, Loch Creran.

Table 3. 4 Grain size analysis data for the down-core sediment samples at stations 02, 03, 04, 06 and 08, Loch Creran.

Core ID	*Interval (cm)*	*Mean Particle Size*	*% Clay*	*% Silt*	*% Sand*
SC-02-A	2-3 cm	72.58	17.10	48.29	34.57
	4-5 cm	63.32	20.19	49.94	29.86
	6-7 cm	59.70	20.88	50.56	28.55
	8-9 cm	58.48	20.60	51.40	27.92
	10-11 cm	55.17	20.81	52.02	27.08
	12-13 cm	51.74	21.80	55.01	23.27
	14-15 cm	53.69	21.29	53.25	25.36
SC-03-A	2-3 cm	75.43	12.18	44.44	43.30
	4-5 cm	71.09	13.45	47.34	39.16
	6-7 cm	67.67	14.33	49.58	36.11
	8-9 cm	61.77	15.88	52.77	31.36
	10-11 cm	48.36	18.35	56.60	25.05
	12-13 cm	55.85	18.82	56.22	24.97
	14-15 cm	39.11	22.41	59.98	17.65
SC-04-B	2-3 cm	60.18	14.93	49.00	36.01
	4-5 cm	59.74	16.99	49.44	33.50
	6-7 cm	59.63	15.67	51.97	32.28
	8-9 cm	56.79	19.03	51.03	29.90
	10-11 cm	58.65	16.94	53.28	29.89
	12-13 cm	57.74	17.86	55.38	26.40
	14-15 cm	40.83	20.53	60.60	18.90
SC-06-A	2-3 cm	68.21	14.08	51.29	34.60
	4-5 cm	80.27	13.53	48.03	38.44
	6-7 cm	82.54	11.38	45.97	42.63
	8-9 cm	79.13	11.81	46.53	41.73
	10-11 cm	63.72	14.32	53.17	32.63
	12-13 cm	67.26	12.51	51.97	35.49
	14-15 cm	55.83	16.42	55.57	27.90
SC-08-A	2-3 cm	49.89	15.60	62.35	22.08
	4-5 cm	55.79	14.06	60.42	25.56
	6-7 cm	53.58	14.51	59.73	25.78
	8-9 cm	51.86	16.08	60.88	23.04
	10-11 cm	51.08	18.68	61.53	19.84

3.4 Organic matter (OM) content

The most universal of environmental disturbances which may be loosely termed ‘marine pollution’ and the best documented is that of the organic ‘enrichment’ of marine waters (Pearson and Rosenberg, 1978). Organic matter (OM) is composed mainly of organic carbon, nitrogen, oxygen, phosphorus and Sulphur, is the most important component in the marine environments, and provides energy for most of the biological reactions (Libes, 1992). Sediment organic carbon (OC) content is probably the most practical descriptor of organic enrichment and it is also used as an environmental reference parameter for biomonitoring methods (e.g., Borja et al., 2003). It was frequently assumed, via many authors, that the faunal response to any sudden change in organic enrichment introduced into the marine environment must be considered into account and is a representative for most types of pollution (e.g., Hily, 1984; Glémarec et al., 1986; Borja et al., 2000; Rosenberg et al., 2004; Muxika et al., 2007). Therefore, studying this component in the seabed can reveal if increase productivity of these compounds had a precise impact on the benthic environment (Ludwig, 2001).

To evaluate the impacts of these organic loads on benthic communities, twenty surface samples (including the replicate samples) across Loch Creran have been used to measure the OM content. The surface samples were

collected during May 2016 and May 2018 sampling cruises. Seventeen of them were in the main basin (beneath and around fish farming cages) and three were in the upper basin (River Creran). For the determination of organic carbon concentration and to study the response of benthic foraminifera to this environmental parameter (see chapter 4), a quantitative analysis of the sediments was carried out to reflect the level of impact of these organic inputs.

3.4.1 Methods for organic matter (OM) content measurements

There are several methods to measure OM content, two of which are most often used: elemental analysis (EA), and the loss of weight on ignition (LOI) method (e.g., Buchanan, 1984). While the initial method (i.e., TOC measurement) is more accurate and has been broadly used (e.g., Luczak et al., 1997), the LOI method is still largely used in benthic ecology because it is quick and cheap (e.g., Mook and Hoskin, 1982). In this study, and for accurate determination of the organic carbon (OC) content in the sediment, the first procedure (elemental analysis - EA) was applied to the surface samples. Loss of weight on ignition (LOI) technique was also used in this study and was applied for the down-core samples in order to determine the percentages of labile, refractory and total organic matter (TOM). Heiri et al., (2000) provide a review of the LOI process. The % labile OM was defined as the percentage weight loss of the sediment sample after combustion at 250°C and the %

refractory organic matter is the weight loss of the sediment sample after combustion at 500°C (Kristensen, 1990). This method is well documented (Cauwet, 1975, Kristensen & Andersen, 1987; Telek & Marshall, 1974; Hedges & Stern, 1984; Hirota & Szyper, 1976; Froelich, 1980; Byers et al., 1978). This method also included the quantification of the isotopic signatures in the bulk OM in the sediment. In this study, each sample was analysed for total organic carbon (TOC), organic carbon (%OC), inorganic carbon (%IC), total nitrogen (TN) as well as stable N- and C isotopes. Table 3.5 represents the concentration of each isotope in all surface samples.

Table 3. 5 Stations, water depths and the values of organic carbon (OC) and related organic elements expressed as relative abundances of the surface sediment samples, Loch Creran.

Sediment ID code	*Latitude*	*Longitude*	*Depth (m)*	*%TC*	*%OC*	*%IC*	*%N*	*%H*	*%S*	*OC/N*
CC-01-A	56° 31.141	5° 22.386	37.00	2.95	2.85	0.10	0.19	0.62	0.59	17.50
CC-01-B	56° 31.134	5° 22.299	37.00	2.93	2.31	0.62	0.22	0.66	0.25	12.25
CC-01-C	56° 31.133	5° 22.298	38.00	2.56	2.18	0.38	0.16	0.50	0.15	15.90
CC-02-A	56° 31.372	5° 21.434	29.90	3.90	3.50	0.40	0.25	0.69	0.47	16.33
CC-02-B	56° 31.372	5° 21.437	30.00	4.66	3.74	0.92	0.29	0.71	0.52	15.05
SC-02-A	56° 31.373	5° 21.436	27.20	3.15	2.59	0.56	0.22	0.62	0.33	13.73
SC-03-A	56° 31.373	5° 21.466	29.10	2.38	2.32	0.06	0.16	0.50	0.35	16.92
CC-03-A	56° 31.377	5° 21.466	29.20	3.17	2.79	0.38	0.21	0.59	0.40	15.50
CC-03-B	56° 31.376	5° 21.465	29.00	3.80	2.73	1.07	0.19	0.59	0.37	16.76
SC-04-A	56° 31. 368	5° 21. 475	29.80	3.09	2.87	0.22	0.42	0.58	0.59	7.97
SC-04-B	56° 31.370	5° 21.478	29.70	2.51	2.32	0.19	0.34	0.47	0.41	7.96
SC-05-A	56° 31.359	5° 21. 565	30.10	2.57	1.90	0.67	0.24	0.61	0.33	9.24
SC-06-A	56° 31.486	5° 21.167	27.40	5.73	4.46	1.27	0.30	0.77	0.48	17.34
SC-07-A	56° 31.483	5° 21.147	24.80	2.89	2.69	0.20	0.19	0.57	0.31	16.52
SC-08-A	56° 31.520	5° 21.065	23.00	2.24	1.66	0.58	0.14	0.55	0.20	13.83
GB-03-C	56° 33.188	5° 15.130	12.50	8.02	4.18	3.83	0.42	1.86	0.60	11.63
GB-07-A	56° 33.010	5° 15.072	13.70	7.21	5.11	2.09	0.44	1.55	0.53	13.55
GB-09-A	56° 32.937	5° 15.549	22.70	7.04	4.62	2.41	0.50	1.57	0.26	10.79
GB-20-A	56° 31.430	5° 20.220	17.50	2.25	1.89	4.35	0.15	0.62	0.20	14.70
GB-28-A	56° 31.293	5° 22.694	29.60	2.32	0.98	1.33	0.11	0.47	0.16	10.40

3.4.2 Results and discussion

3.4.2.1 Organic carbon content (OC) of the surface samples

Large differences in the OC content of surface sediments were observed between the samples stations. Based on the analytical data, Table 3.5, the OC measurements differ notably between the selected sample stations. The results potentially allow areas susceptible to organic stress to be identified, especially where %OC is elevated above 4%. Figure 3.5 illustrates the graphical distribution of the %OC contents of the surficial sediments throughout the study area.

Depending on the analysis of data set, it is obvious that samples from the upper basin (river influenced) exhibit the characteristics of a highly organic-rich (impacted) environment. This is due to OC sequestered within the loch through oxidative and depositional processes (Loh. et. al., 2010). In addition, most of the fish farms samples exhibit the organic contents characteristics of high to moderately-impacted environments. It was expected that the amount of organic waste released into the water surrounding a fish farm is proportional to fish activity. The most evident changes in the benthic habitat at these stations were the large accumulations of the organic contents and a strong reduction of redox potential values (DO_2); these results and their

impact upon foraminiferal assemblages are discussed later (Chapter 4). However, the values for the organic contents at the other stations (away from the farming sites) changes noticeably with changing distance from the fish farming sites. Stations, 01, 08, 12 and 13, illustrate that the values for the organic contents have decreased and support the results related to increase in foraminiferal density at these stations (Chapter 4).

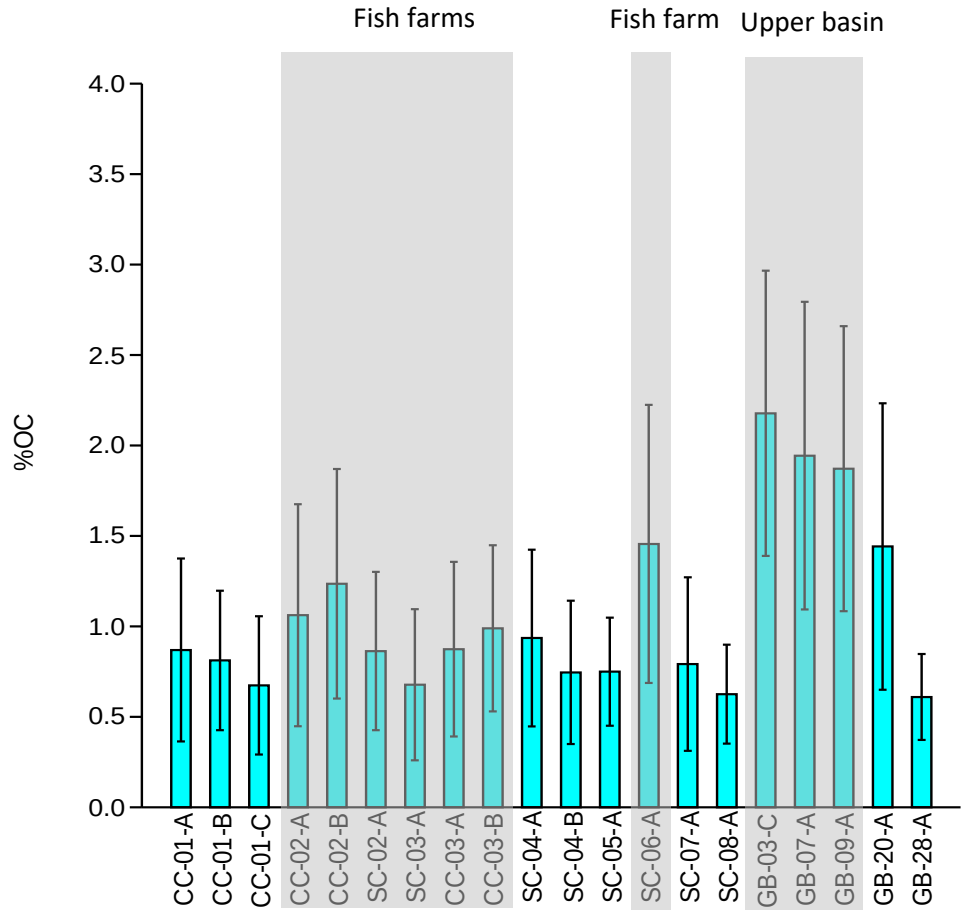

Figure 3. 4 The spatial distribution pattern of the organic carbon (%OC) for the surface sediment samples in Loch Creran (see figure 2.3 to locate these examples).

3.4.2.2 Organic matter (OM) content of the down-core samples.

The down-core organic matter (OM) analysis was performed on the cores which were related specifically to the study of the temporal distribution of foraminifera (Chapter 5). The OM percentage and carbon/nitrogen elemental ratios for the down-core sediment samples are shown in Table 3.6 (for fish farming sites) and Table 3.7 (for the non-fish farming sites). We followed the elemental analysis (EA) procedure of measuring the organic matter content mentioned earlier (see chapter 2) for analysis of the down-core sediment samples. At the fish farm stations, the upper sediment samples from all cores were predominantly dark in colour. The lighter, homogenous brown sediments were observed, typically at depths below 7 cm which indicates that significant change in TOM contents in the sediments of Loch Creran adjacent to the fish farm sites occurred at this depth. Figure 3.5 illustrates the curve for the OM content related to the stations which illustrate these down-core changes (e.g. cores SC-02-A, SC-03-A and SC-06-A). At these sites, from 4 - 7 cm core depth, the %TOM content increased upward to its highest recorded value in the surface or near-surface sample. This trend was observed for most of the cores located close to the fish cages. A stable %TOM contents is typically observed below 7 cm core depth, coinciding with a change in sediment colour from dark to light brown.

Table 3. 6 Sedimentary organic matter (OM) data for the down-core fish farm stations, Loch Creran.

Core id code	Depth intervals	TOM	N [%]	C [%]	C/N ratio
SC-02-A	2-3 cm	9.31	0.11	4.09	43.38
	3-4 cm	7.97	0.31	4.96	18.67
	4-5 cm	10.17	0.45	4.59	11.90
	5-6 cm	7.96	0.39	5.26	15.74
	6-7 cm	6.89	0.18	3.95	25.60
	7-8 cm	6.88	0.28	4.32	18.00
	8-9 cm	6.65	0.31	2.66	10.01
	9-10 cm	5.90	0.15	2.63	20.46
	10-11 cm	6.16	0.31	2.27	8.54
	11-12 cm	6.11	0.3	2.26	8.79
	12-13 cm	6.05	0.28	2.52	10.50
	13-14 cm	6.34	0.32	2.42	8.82
SC-03-A	2-3 cm	5.77	0.16	2.42	17.65
	3-4 cm	5.95	0.18	2.39	15.49
	4-5 cm	6.21	0.23	2.51	12.73
	5-6 cm	6.17	0.21	2.81	15.61
	6-7 cm	6.18	0.17	2.22	15.24
	7-8 cm	5.99	0.15	2.59	20.14
	8-9 cm	5.27	0.16	2.37	17.28
	9-10 cm	5.23	0.17	2.37	16.26
	10-11 cm	5.67	0.15	2.16	16.80
	11-12 cm	5.29	0.12	2.05	19.93
	12-13 cm	5.00	0.17	2.41	16.54
	13-14 cm	4.50	0.16	2.11	15.39
SC-06-A	2-3 cm	8.80	0.37	7.11	22.42
	3-4 cm	8.42	0.38	3.39	10.41
	4-5 cm	7.96	0.35	3.39	11.30
	5-6 cm	6.10	0.56	3.69	7.69
	6-7 cm	6.05	0.35	3.04	10.13
	7-8 cm	5.29	0.35	2.77	9.23
	8-9 cm	4.98	0.31	2.7	10.16
	9-10 cm	4.64	0.36	1.84	5.96
	10-11 cm	4.90	0.15	2.83	22.01
	11-12 cm	4.66	0.2	2.48	14.47
	12-13 cm	4.65	0.25	2.57	11.99
	13-14 cm	4.86	0.32	2.56	9.33

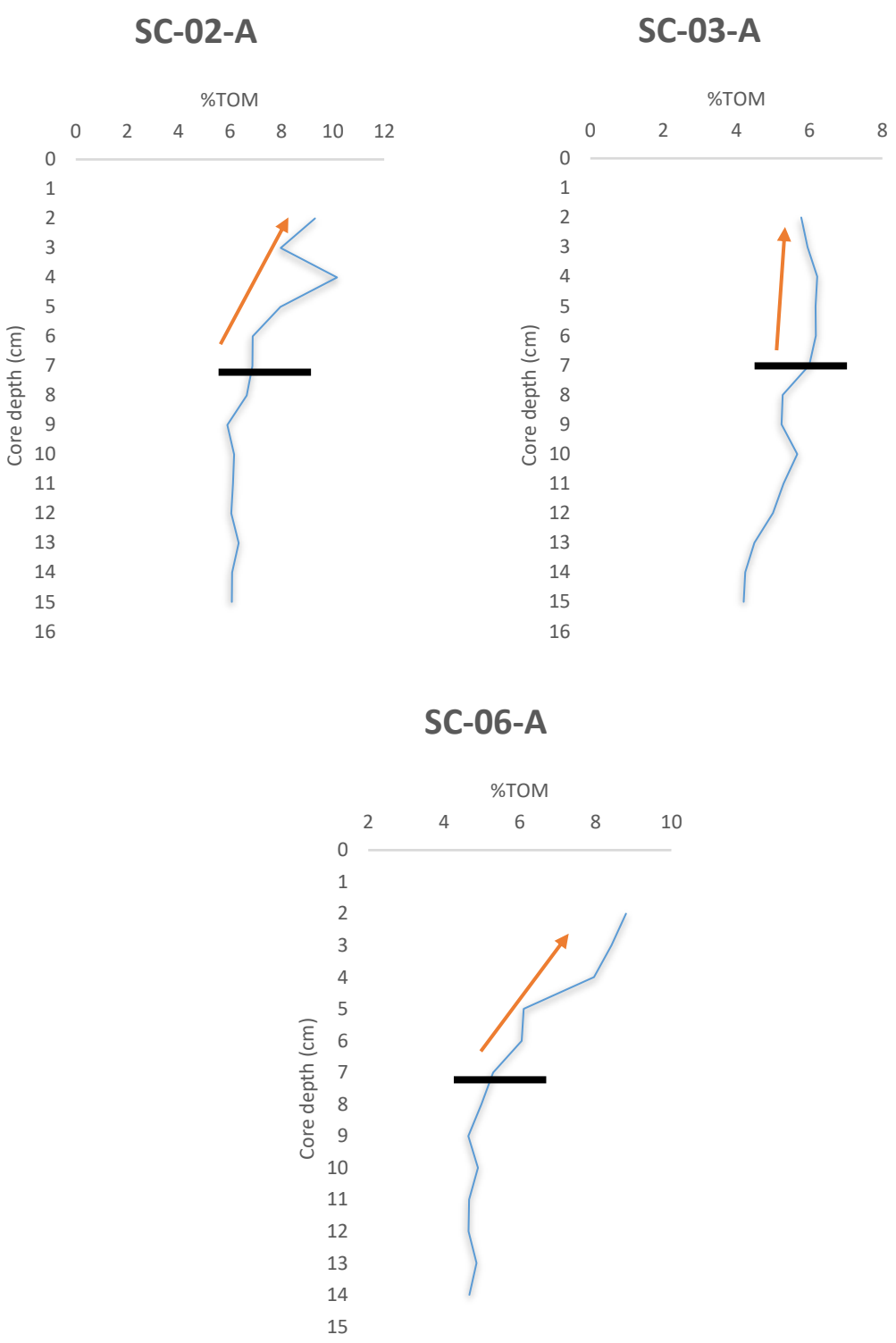

Figure 3. 5 Down-core %TOM content for Loch Creran sampling stations beneath fish farming sites; note the marked increase in % TOM above 7 cm core depth.

At the non-fish farming sites (cores SC-04-B and SC-08-A) the sub-surface sediments were an even brown colour and undisturbed in both cores. Bivalve shell fragments were also visible in some of the down-core sediment samples; these were largely absent from the fish farming sites. Figure 3.6 illustrates the %TOM content plot for the two cores as a representative for the non-fish farming sites. As illustrated in the figure, the down-core %TOM curve for both stations is almost stable from the surface sediment layer to the bottom of each core. The %TOM values range from 4.56 to 6.09% and from 5.18 to 6.59% in SC-04-B core and SC-08-A core, respectively.

Table 3. 7 Sedimentary organic matter (OM) data for the non-fish farming stations, Loch Creran. Core SC-04-B, for which down-core measurements exist, was chosen for further down-core foraminiferal assemblages counting; since there were no data available for SC-08-A.

Core id code	*Core depth*	*TOM*	*N [%]*	*C [%]*	*C/N ratio*
SC-04-B	2-3 cm	5.88	0.19	2.12	13.02
	3-4 cm	6.09	0.21	2.85	15.83
	4-5 cm	5.90	0.22	2.61	13.84
	5-6 cm	5.78	0.16	2.53	18.45
	6-7 cm	5.28	0.15	2.43	18.9
	7-8 cm	5.01	0.19	2.24	13.75
	8-9 cm	5.33	0.15	1.94	15.09
	9-10 cm	5.39	0.13	1.95	17.5
	10-11 cm	4.56	0.09	1.38	17.89
	11-12 cm	4.82	0.09	1.38	17.89
	12-13 cm	5.13	0.12	1.81	17.6
	13-14 cm	5.64	0.08	1.79	26.1
	14-15 cm	5.62	0.19	2.25	13.82
SC-08-A	1-2 cm	6	0.24	2.24	18.67
	2-3 cm	6.00	0.12	1.8	17.5
	3-4 cm	5.88	-	-	-
	4-5 cm	5.27	-	-	-
	5-6 cm	5.56	-	-	-
	6-7 cm	5.18	-	-	-
	7-8 cm	5.46	-	-	-
	8-9 cm	5.92	-	-	-
	9-10 cm	6.59	-	-	-
	10-11 cm	6.59	-	-	-

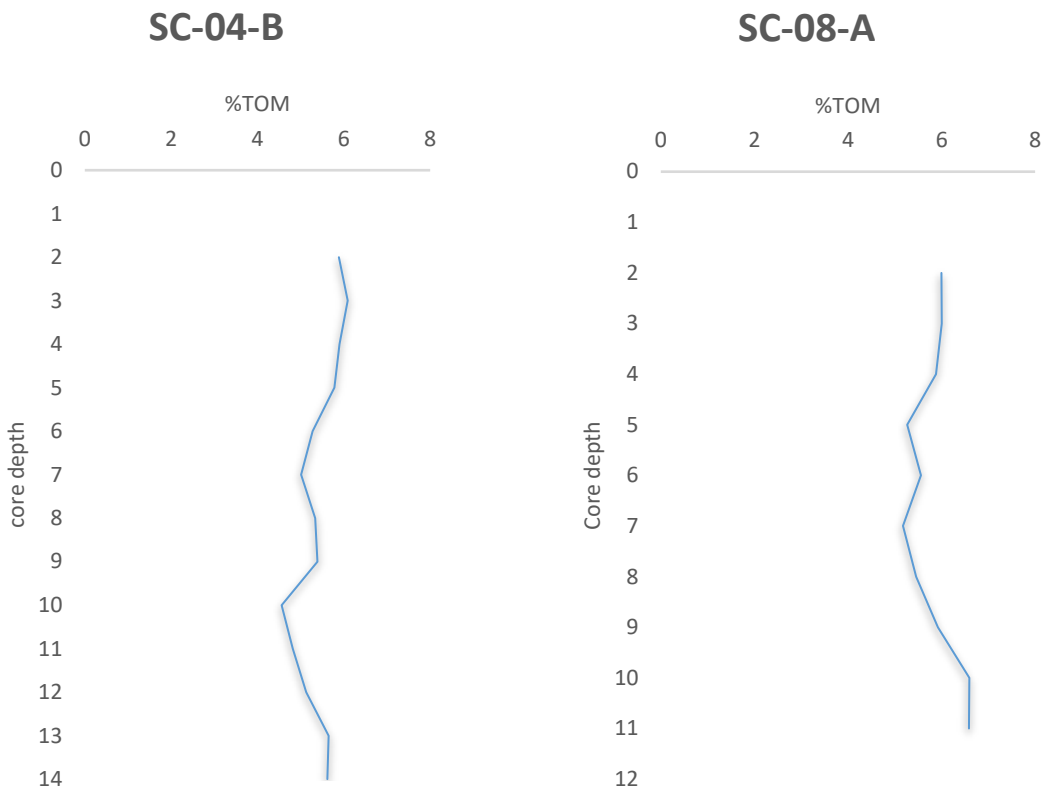

Figure 3. 6 Down-core %TOM content at the non fish farming sites; note the relatively stable %TOM content throughout each core.

3.5 Conclusion

A quantitative analysis of the OM content has been applied to provide an understanding of the distribution of the OM in the sediments of Loch Creran. This understanding is crucial, as it is a prerequisite for studies that assess how biodiversity and species ranges change in response to abrupt differences in OM content and accumulation rate (Chapter 4). A restricted exchange (land-locked) and potentially stressed environment was found in the upper basin (River Creran influence), whereas highly OM-enriched environments were found beneath and adjacent to fish farming sites. The results of OM measurements beneath fish farming sites were compared to non-fish farming sites to assess the level of contamination at these environments. The sites which were directly beneath fish cages showed higher sediment OM content as compared to the sites located at a distance from farming areas, thus indicating fish farms to be the dominant source of OM to the sediments. Previous studies have documented elevated levels of OM and nutrients in the sediments directly below fish farms and decreasing concentrations with distance from the point source (e.g., Lee et al. 2006; Loubere P., 1999). This supports the similar pattern in our data with peak levels of OM generally occurring below the fish cages and coinciding with the reduction of the bottom water DO_2 values at these stations. These results

suggest that the most important and perhaps clearest indicator of fish farm activity is an increase of the OM content in the underlying sediments, with the potential to reduce the bottom water DO_2 concentration in the overlying bottom water causes a direct impact on the benthic environment (Chapter 4).

Understanding the down-core distribution pattern of the OM content of these sediments is also important to provide quantitative estimates of the paleoenvironment (Murray, 1991). The results allowed for the comparison of present-day conditions with conditions before the fish farm was established. The results have shown a clear temporal trend in OM changes at specific core depths. The general increase in OM content observed above 7 cm in these cores can be correlated with fish farms production which started in 1983 in Loch Creran and has gradually increased and continued until present day, giving reason to believe that the increase of the OM content is indeed related to the fish farm activity. The down-core OM results offer the potential to be correlated with the temporal (down-core) distribution pattern of benthic foraminifera to provide an opportunity to understand the pre-and post-impacted status of the environment in response to the onset of fish farming (Chapter 5).

CHAPTER 4

SPATIAL DISTRIBUTION OF MODERN BENTHIC FORAMINIFERA IN LOCH CRERAN

CHAPTER 4

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4.1 Introduction

Foraminifera are important components within benthic marine biological communities and can be useful indicators of the overall health of a marine environment (Alve, 1995; Pati and Patra, 2011). They are important faunal communities of most marine environments as result of their abundance and distribution (Lee et al., 1985). They provide one of the most sensitive and competitive faunal biomarkers available for indicating any changes in marine environments, being quick to respond to changes in environmental conditions (Culver and Buzas, 1995; Buzas et al. 2003). In palaeoecological research, modern foraminiferal distributions have been used to help to understand the marine environmental changes in both the present and geological past (Sen Gupta, 1999). However, few studies have been carried out to assess how organic matter loading modifies benthic ecosystem functions. In this study, an investigation of how different natural and anthropogenic environmental stresses (specifically, organic enrichments to marine sediments) impacts the distribution of benthic foraminifera has been undertaken.

Mapping and understanding the response of benthic foraminiferal communities will help to develop new approaches to evaluating and monitoring the quality status of the marine environment. Fish farms in Loch Creran, on the west coast of Scotland, were selected as a representative type of such locally impacted marine habitats. The most evident effects of fish farms on the bottom sediments are the accumulation of organic matter (OM) (Holer, 1991; Henderson et al., 1997; Karakassis *et al.,* 1998). At the same time, rivers (notably in the upper basin of Loch Creran) are considered to be an important, additional source of land-derived organic carbon to Loch Creran (Loh P. S. *et al*., 2008).

4.2 Taxonomy

In order to describe and validate the distribution pattern and biodiversity of foraminifera it is essential to establish a reliable taxonomic foundation from which foraminiferal individuals can be easily and consistently identified. They are essentially described using their external morphological characteristics. Classical taxonomy (based on wall structure) has shaped the current understanding of the distribution and biodiversity of foraminifera (Murray, 2001). In this study, foraminifera were identified according to Loeblich and Tappan (1988) with the assistance of unpublished descriptions and images from Austin (1991).

4.3 Distribution of benthic foraminifers

To study the spatial distribution pattern of benthic foraminiferal assemblages, a uniform sample interval of the uppermost sediment (0_1 cm) layer was chosen to obtain comparable frequency data for the foraminiferal species in all investigated areas (see chapter 2). In order to validate and understand how modern benthic foraminifera respond to environmental changes, it is important to understand how these species are influenced by different environmental parameters such as temperature, water depth, dissolved oxygen (DO_2) and grain size analysis as well as the inputs of organic matter (OM). The selection of the sampling sites from where surface sediment samples are collected is important to assess the quality status of the marine ecosystem (QSE). The details of the sampling stations of this study area are summarized in table 4.1 and figure 4.1. The benthic foraminiferal assemblages of the studied samples have been identified and quantitavely analysed. The quantitative count data were used to calculate community statistics such as the total number of species (N), Shannon diversity index (H) and Fisher alpha diversity index (α). The results are documented in Appendix 1. It should be noted that the data comprise counts of the number of individuals belonging to a total of 42 benthic foraminiferal species from 20 surface samples.

Published literature on benthic foraminiferal distribution on the west coast of Scotland is limited. Most of these studies were devoted to the areas around NW Scotland (e.g.; Heron-Allen and Earland 1916, Hannan & Rogerson, 1997). Heron-Allen and Earland (1916) had some samples from deeper water to the west of Scotland, most were from the inner shelf, and their faunas include diverse milliolids. They recorded 324 benthic species and varieties, 27 of which were new records for British seas. Conversely, the work of Murray (2003) was devoted to a study of the distribution of benthic foraminifera on the Hebridean Shelf and in Loch Etive, west Oban, Scotland (e.g.; Murray (2003) and Murray et al., 2003).

Table 4. 1 Stations of Loch Creran surface sediment samples (main basin) selected for foraminiferal analysis.

Stations	*Sample ID code*	*Latitude, N*	*Longitude, W*	*Depth [m]*	*BWT °C*	*% Organic matter*	*Mean/Median grain size ratio*	*Skewness*	*Kurtosis*
Station 01	CC-01-A	56° 31.141	5° 22.386	37.00	12.6	2.85	1.56	4.52	29.61
	CC-01-B	56° 31.134	5° 22.299	37.00	12.6	2.31	2.05	3.61	14.62
	CC-01-C	56° 31.133	5° 22.298	38.00	12.6	2.18	1.57	2.55	7.96
Station 02	CC-02-A	56° 31.372	5° 21.434	29.90	12	3.50	1.92	2.87	10.15
	CC-02-B	56° 31.372	5° 21.437	30.00	12	3.74	1.55	2.60	9.26
	SC-02-A	56° 31.373	5° 21.436	27.20	12	3.94	1.84	3.14	12.50
Station 03	SC-03-A	56° 31.377	5° 21.465	29.20	11.7	2.59	1.57	3.91	20.32
	CC-03-A	56° 31.376	5° 21.465	29.00	11.7	2.79	1.66	3.31	14.43
	CC-03-B	56° 31.375	5° 21.464	29.10	11.7	2.73	1.61	2.68	8.91
Station 04	SC-04-A	56° 31.368	5° 21.475	29.80	11.2	2.87	1.50	2.81	9.62
	SC-04-B	56° 31.370	5° 21.478	29.70	11.2	2.32	1.54	3.98	23.26
Station 05	SC-05-A	56° 31.359	5° 21.565	30.10	11.9	1.90	1.49	3.01	11.33
Station 06	SC-06-A	56° 31.486	5° 21.167	27.40	12.1	4.46	1.88	4.46	25.20
Station 07	SC-07-A	56° 31.483	5° 21.147	24.80	11.4	2.69	1.47	2.94	10.54
Station 08	SC-08-A	56° 31.520	5° 21.065	23.00	10.8	1.66	1.43	3.55	16.35
Station 09	GB-03-C	56° 33.188	5° 15.130	12.50	-	4.18	1.55	2.89	10.59
Station 10	GB-07-A	56° 33.010	5° 15.072	13.72	-	5.11	1.59	1.58	2.31
Station 11	GB-09-A	56° 32.937	5° 15.549	22.70	-	4.62	1.64	2.12	5.13
Station 12	GB-20-A	56° 31.430	5° 20.220	17.60	-	1.89	2.05	4.88	31.69
Station 13	GB-28-A	56° 31.293	5° 22.694	29.60	-	0.98	1.30	2.17	8.36

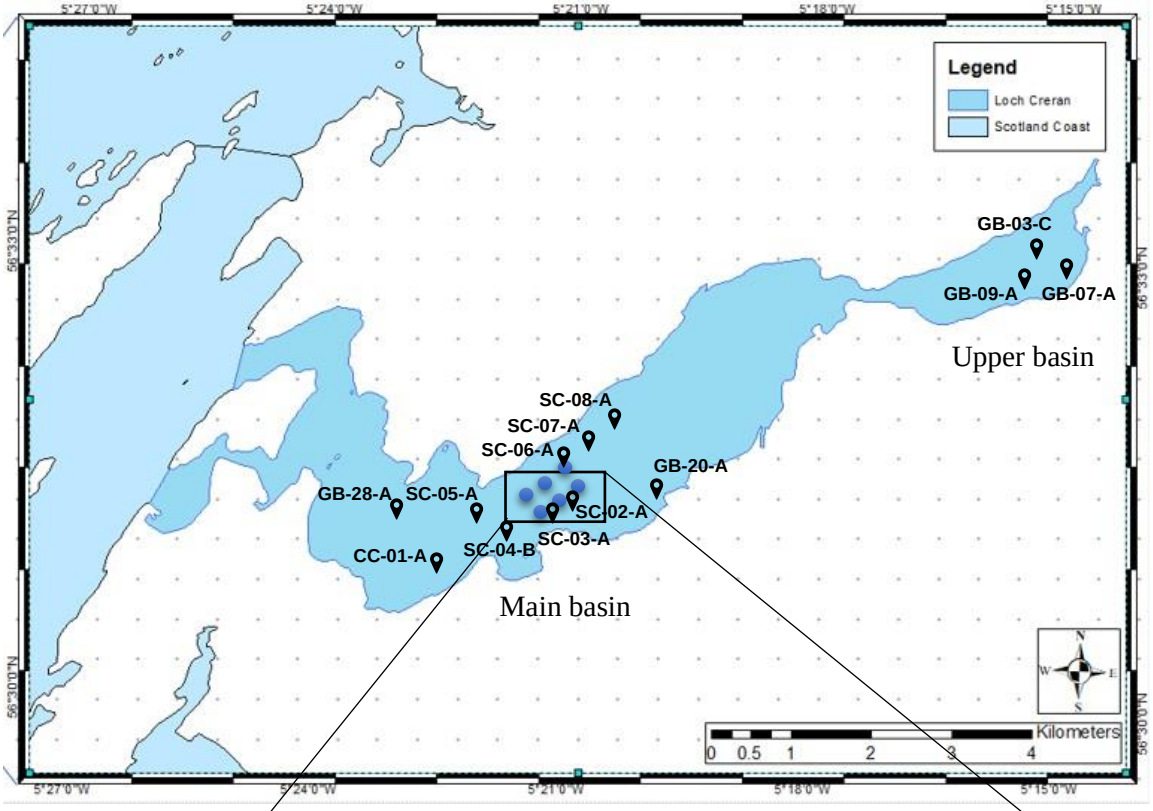


Figure 4. 1 Locatoion map illustrating the positions (the main basin and the upper basin), including the fish farming sites (see inset photograph) of the Loch Creran surface samples obtained for foraminiferal analysis.

4.4 Methods

The distribution of foraminiferal assemblages in Loch Creran were assessed by analysing 20 surface sediment samples that were collected from thirteen different stations using a van Veen grab (GB), Craib corer (CC) and a Sholkovitch corer (SC). Samples were stored in freezer until processed (Chapter 2). The positions and water depths of these samples can be seen in Table 4.1 and figure 4.1. The depth, bottom water temperature (BWT) were noted later in SAMS laboratory after sample collection, the grain size and the percentage of organic matter (%OM) analyses were carried out on associated sediment samples. Although several studies have utilized 100 and 150 specimen counts to identify and map foraminiferal compositions and associations, (Hayward et al., 1996; Hallock-Muller and Williams, 2000), in this study, counts of 300 specimens per sample was utilised (Murray, 1973).

Due to low numbers of stained foraminiferal specimens in Loch Creran surface sediment, the total assemblages have been used throughout. The foraminifera were identified to a species level. Cluster analyses using species-level identifications were used to determine distributional patterns of foraminifera in Loch Creran. Histograms were constructed for organic carbon (OC) contaminants. Correlation analysis was used to determine if the

distribution patterns are related to environmental variables including the OC measurements.

Statistical methods were selected to calculate the species diversity index. The diversity indices were determined by calculating the Fisher-α species diversity and the Shannon-Weaver index. In order to determine any similarities between benthic foraminiferal sample assemblages, the sample assemblages from Loch Creran were subjected to multivariate analyses. A cluster analysis (CA) was created for the interpretation of the assemblages. This method clusters 'similar' data together to classify them into groups, and then ordination techniques to quantify inter-relationships. It is important to mention that this method gives no ecological information; thus, cluster analysis results must interpret quantitavely.

4.5 Results

A total of 42 of modern benthic foraminiferal taxa were identified and recorded from the twenty surface sediment samples in Loch Creran. Taxonomical classification of these species is given in Appendix 1. Seven species were agglutinated taxa, 33 species were hyaline taxa and only 2 species represented the porcelaneous taxa. Count data were transformed into percentage abundance and only those which have a relative abundance of >2

% in the studied area were summarized in the total assemblage. Table 4.2 lists the common benthic foraminiferal species in Loch Creran sorted by the percentage occurrences in samples.

Further statistical analysis was performed on the foraminiferal assemblages for both qualitative and quantitative assessment. The results illustrate that the diversity distribution of foraminifera was relatively high in the sediments at distance from the farming sites, whilst the highest diversity distribution was noted in the sediments at the control station. In contrast, low diversity of foraminiferal tests was found near or directly beneath fish cages (high sediment OM contents), whereas, the lowest diversity was recorded at the upper basin (River influence).

Table 4. 2 Common benthic foraminiferal species in Loch Creran sorted by the maximum abundance (%) all samples. Also shown is the average relative abundance in any one sample across all samples.

Species	*Max abundance %*	*Average relative abundance %*
Eggerella scabra	64.3	34.0
Ammonia beccarii	34.0	24.1
Ammoscalaria runiana	22.0	15.2
Elphidium selseyense	25.7	7.5
Bulimina marginata	7.7	4.2
Asterigerinata mamilla	6.7	1.8
Bulimina elongata	3.3	1.8
Textularia bocki	5.7	1.7
Cibicides lobatulus	5.0	1.5
Reophax scorpiurus	2.7	1.1
Elphidium aculeatum	3.7	0.8
Haplophragmoidesb bradyi	2.0	0.7
Nonionella turgida	3.0	0.6
Oolina williamsoni	2.0	0.6
Reophax scotti	2.7	0.6
Elphidium margaritaceum	1.7	0.5
Fisssurina elliptica	1.7	0.4
Lagena striata	1.3	0.4
Bolivina pseudoplicata	2.3	0.4
Fissurina lucida	1.7	0.3
Oolina melo	1.0	0.2
Oolina hexagona	1.3	0.2
Trochammina sp.	0.7	0.2
Bolivina pseudopunctata	1.0	0.2
Elphidium williamsoni	1.3	0.2
Stanforthia loeblichi	0.7	0.2
Quinqueloculina sp.	0.7	0.2
Elphidium gerthi	1.7	0.1
Elphidium albiumbilicatum	1.3	0.1
Bolivina spathulata	1.0	0.1
Buccella frigida	1.0	0.1
Adercotytryma glomeratume	1.0	0.1
Stanforthia fusiformis	1.3	0.1
Amphicorina scalaris	1.0	0.1
Oolina squamosa	0.3	0.1
Uvigirina perigrina	0.7	0.1

4.5.1 Species relative abundance

In order to determine the relative abundance of benthic foraminifera, a ratio of the number of each species to the sum of the total number of individuals was calculated. This foraminiferal parameter is considered to be an important indicator of the quality status of the sedimentary environment (Schlanger and Douglas, 1973; Thunell, 1976). Thus, it was utilised in this study to evaluate the level of impacts within the study area. The relative abundances of benthic foraminifera are summarized in Table 4.3.

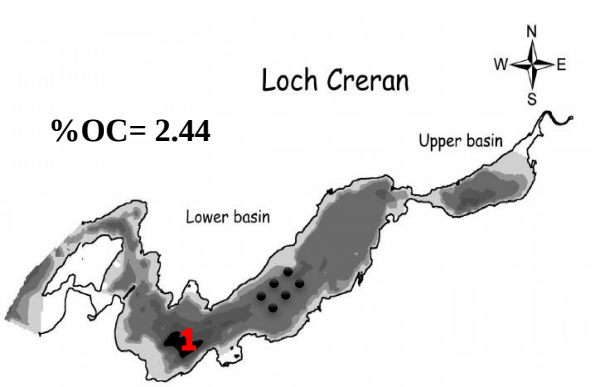
The statistical analysis showed a great variation in the benthic foraminiferal abundance in Loch Creran. The environmental variables of the study area were discussed earlier in this thesis (see chapter 3). The results show that the DO2 concentration were clearly linked to benthic foraminiferal diversities, which were lower at the impacted stations compared to the other sites. Previous studies had reported that foraminifera changed their distribution patter with changing bottom water dissolved oxygen conditions (Alve and Bernhard 1995; Moodley et al. 1998). Additionally, the organic matter load showed the highest values at the impacted sites and is considered to be the most important variable affecting and controlling the abundance and the diversity of benthic foraminifera in Loch Creran. The studies of Jorissen (1988), Samir and El-Din (2001), Hyams-Kaphzan et al. (2008), Romano et

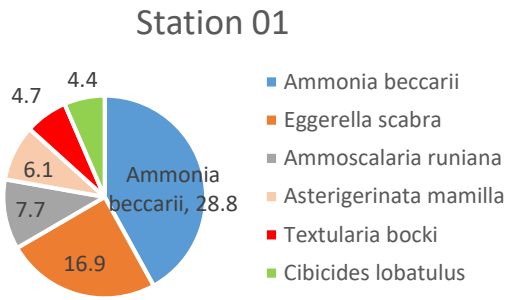
al., 2009, Romano et al., 2013 and (2012) were totally agreed that OM is one of the main control parameter.

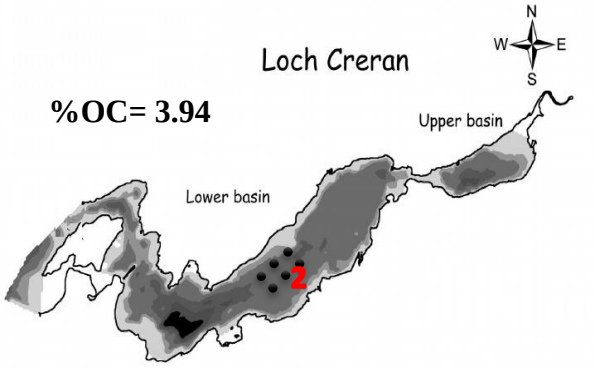
The average relative abundance of the most frequent taxa are listed in Table 4.4 and plotted in Figure 4.2. High abundances of the most common taxa can be found at station 01, representing the reference or the control site (e.g. samples CC-01-A, CC-0-B and CC-01-C). Sediment samples which were collected directly beneath fish farming sites (e.g. stations 02, 03 and 06) and samples collected from the upper basin (e.g. stations 09, 10 and 11) have a relatively low foraminiferal abundance. For those samples which were collected away from the farming cages, the average abundance is calculated to be intermediate (e.g. Stations 04, 05, 07, 08, 12 and 13).

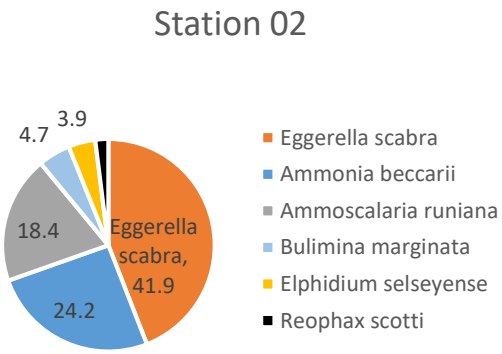
Table 4. 3 The average relative abundance (%) of the most frequent taxa.

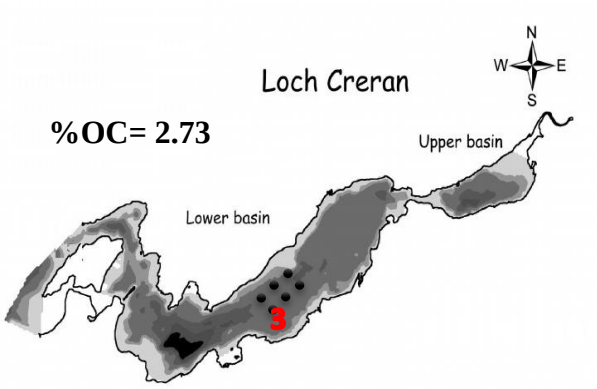
Stations	*Reophax scotti*	*Reophax scorpiurus*	*Ammoscalaria runiana*	*Textularia bocki*	*Eggerella scabra*	*Bulimina elongata*	*Bulimina marginata*	*Asterigerinata mamilla*	*Ammonia beccarii*	*Elphidium selseyense*	*Cibicides lobatulus*
Station 01	0.0	1.8	7.7	4.7	16.9	3.0	2.2	6.1	28.8	2.4	4.4
Station 02	1.9	0.6	18.4	0.1	41.9	1.2	4.7	0.9	24.2	3.9	0.2
Station 03	1.3	1.1	21.1	1.6	37.6	1.2	3.8	1.6	23.8	3.9	0.4
Station 04	0.2	0.8	20.8	1.3	25.8	1.3	5.2	1.3	32.3	4.7	1.2
Station 05	0.0	1.3	18.0	1.3	21.3	2.7	7.0	1.7	34.0	4.7	1.3
Station 06	0.3	0.7	19.3	0.0	43.0	0.0	4.7	0.3	25.0	5.0	0.0
Station 07	0.7	2.3	18.3	1.3	25.0	0.3	7.7	1.7	30.0	7.3	0.0
Station 08	0.0	2.7	15.0	3.3	18.0	1.3	6.7	2.3	28.7	6.0	3.0
Station 09	0.0	0.0	2.3	0.0	64.3	2.7	1.3	0.0	3.3	24.0	0.0
Station 10	0.0	0.0	2.7	0.0	63.3	3.3	1.7	0.0	2.7	25.7	0.0
Station 11	0.0	0.0	3.3	0.0	61.7	3.0	2.0	0.0	5.3	23.0	0.3
Station 12	0.0	1.3	21.7	2.7	21.7	2.0	5.7	0.3	28.3	8.0	2.7
Station 13	0.0	1.3	20.0	3.7	20.7	1.3	5.3	1.3	29.0	6.7	4.7

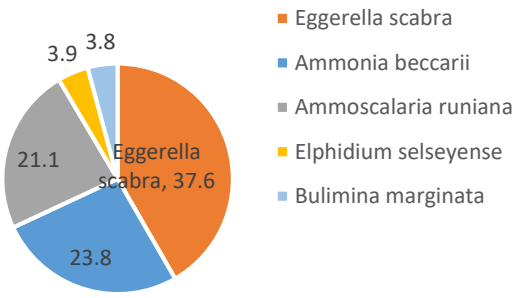

Loch Creran
%OC= 2.44
N
W
E
S
Upper basin
Lower basin
1

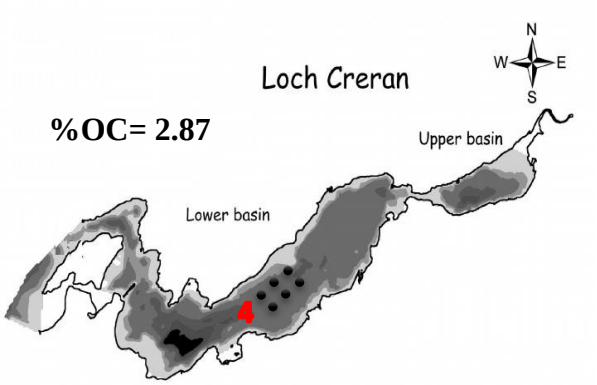

Station 01
4.4
4.7
6.1
7.7
16.9
Ammonia beccarii, 28.8
Ammonia beccarii
Eggerella scabra
Ammoscalaria runiana
Asterigerinata mamilla
Textularia bocki
Cibicides lobatulus

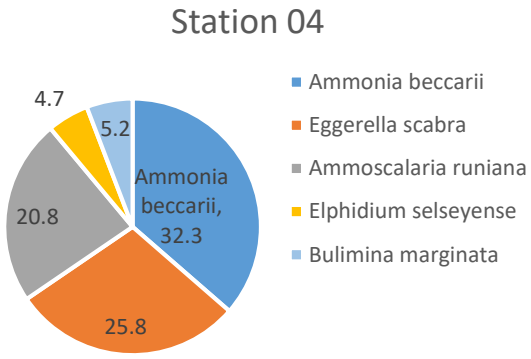

Loch Creran
%OC= 3.94
N
W
E
S
Upper basin
Lower basin
2

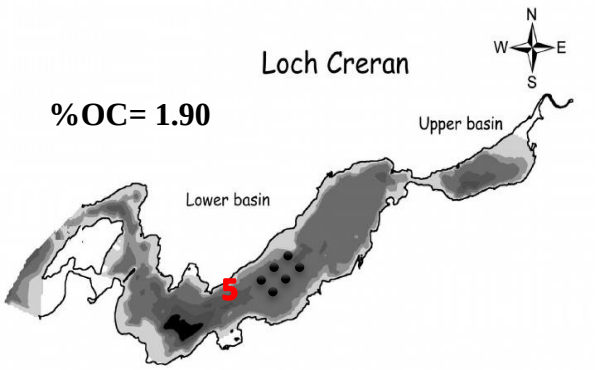

Station 02
3.9
4.7
18.4
24.2
Eggerella scabra, 41.9
Eggerella scabra
Ammonia beccarii
Ammoscalaria runiana
Bulimina marginata
Elphidium selseyense
Reophax scotti

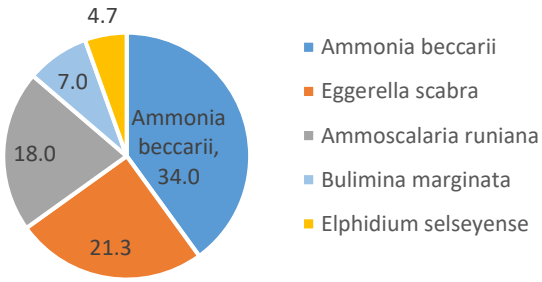

Loch Creran
%OC= 2.73
N
W
E
S
Upper basin
Lower basin
3

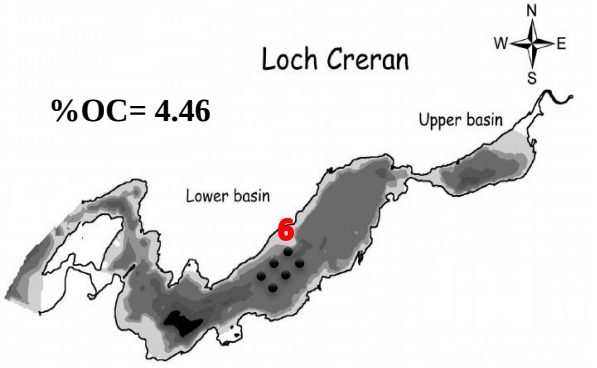

Station 03
3.9
3.8
21.1
23.8
Eggerella scabra, 37.6
Eggerella scabra
Ammonia beccarii
Ammoscalaria runiana
Elphidium selseyense
Bulimina marginata

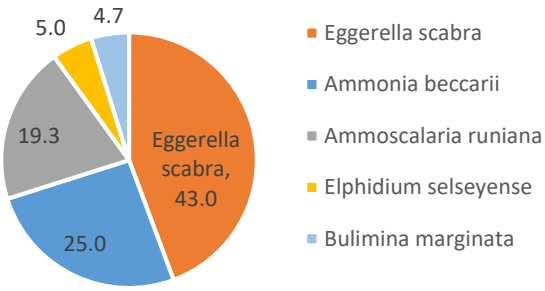

Loch Creran
%OC= 2.87
N
W
E
S
Upper basin
Lower basin
4

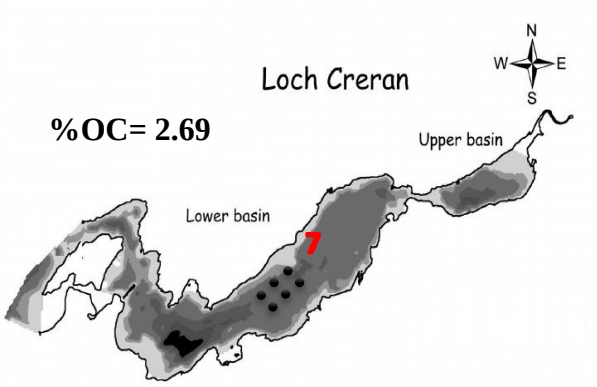

Station 04
4.7
5.2
Ammonia beccarii, 32.3
20.8
25.8
Ammonia beccarii
Eggerella scabra
Ammoscalaria runiana
Elphidium selseyense
Bulimina marginata

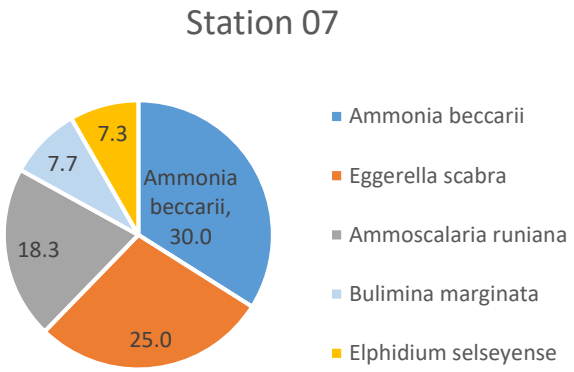

Loch Creran
%OC= 1.90
N
W
E
S
Upper basin
Lower basin
5

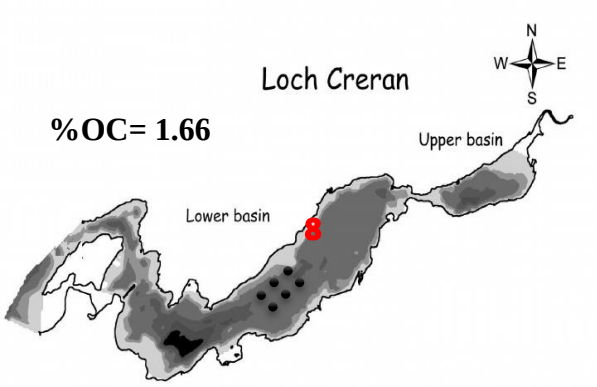

Station 05
4.7
7.0
Ammonia beccarii, 34.0
18.0
21.3
Ammonia beccarii
Eggerella scabra
Ammoscalaria runiana
Bulimina marginata
Elphidium selseyense

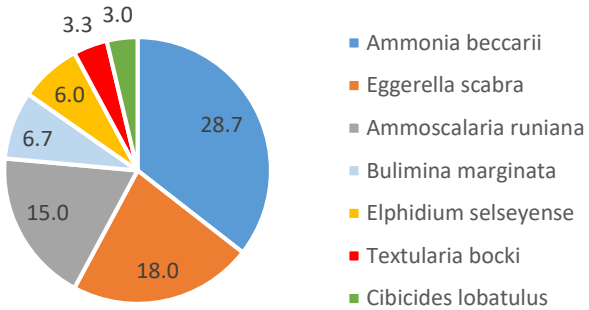

Loch Creran
%OC= 4.46
N
W
E
S
Upper basin
Lower basin
6

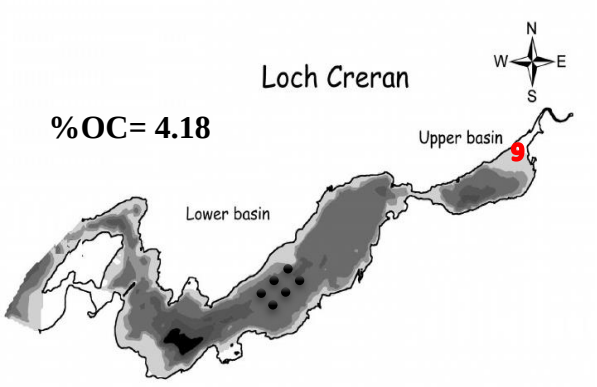

Station 06
5.0
4.7
Eggerella scabra, 43.0
19.3
25.0
Eggerella scabra
Ammonia beccarii
Ammoscalaria runiana
Elphidium selseyense
Bulimina marginata

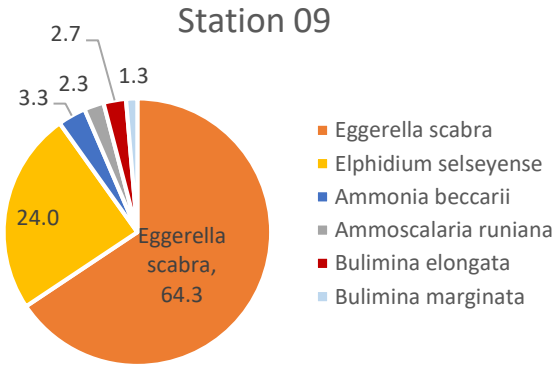

Loch Creran
%OC= 2.69
Upper basin
Lower basin
7
N
W
E
S

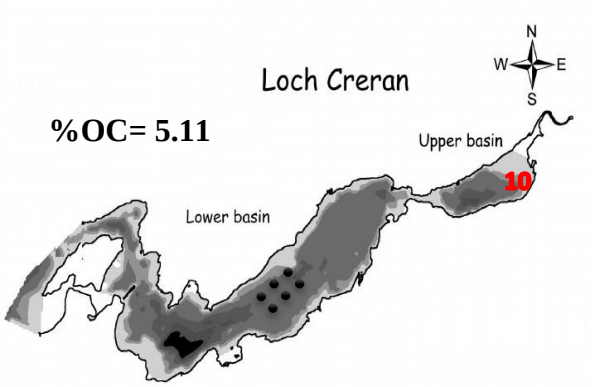

Station 07
Ammonia beccarii, 30.0
25.0
18.3
7.7
7.3
Ammonia beccarii
Eggerella scabra
Ammoscalaria runiana
Bulimina marginata
Elphidium selseyense

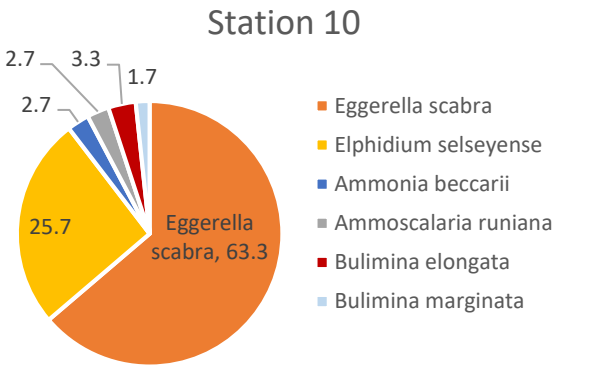

Loch Creran
%OC= 1.66
Upper basin
Lower basin
8
N
W
E
S

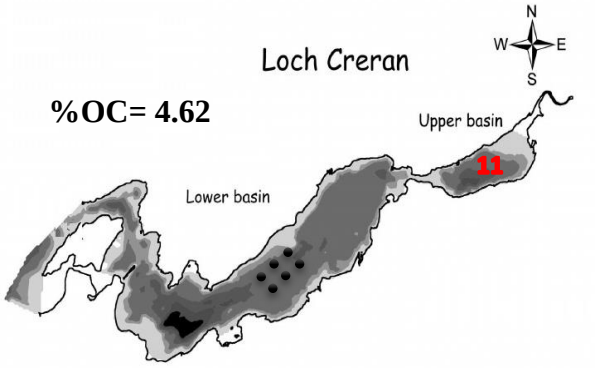

Station 08
28.7
18.0
15.0
6.7
6.0
3.3
3.0
Ammonia beccarii
Eggerella scabra
Ammoscalaria runiana
Bulimina marginata
Elphidium selseyense
Textularia bocki
Cibicides lobatulus

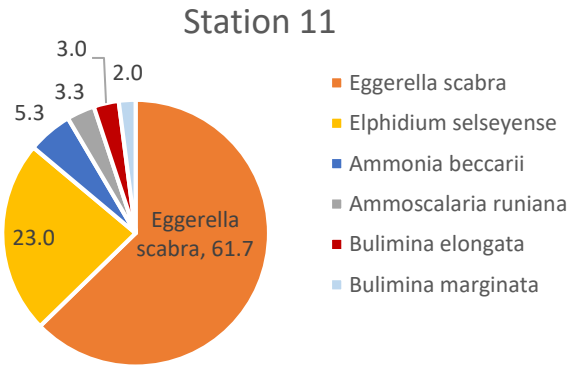

Loch Creran
%OC= 4.18
Upper basin
Lower basin
9
N
W
E
S

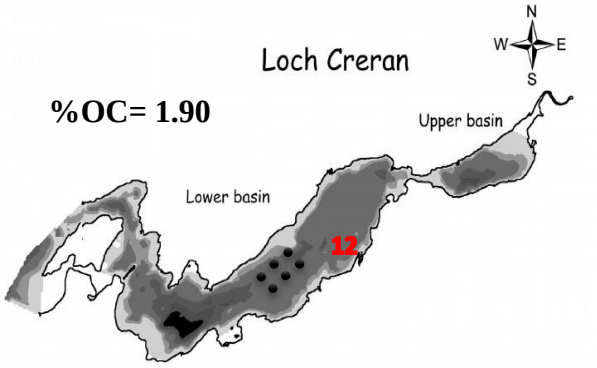

Station 09
Eggerella scabra, 64.3
24.0
3.3
2.3
2.7
1.3
Eggerella scabra
Elphidium selseyense
Ammonia beccarii
Ammoscalaria runiana
Bulimina elongata
Bulimina marginata

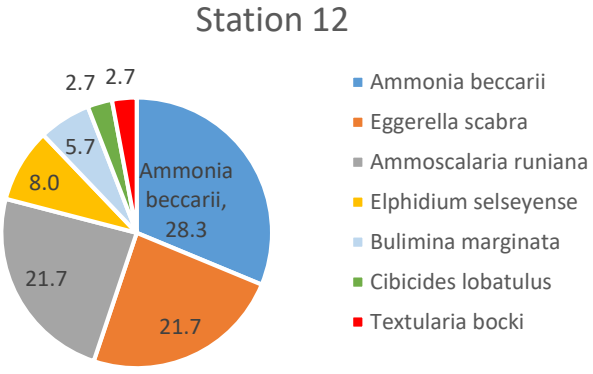

Loch Creran
%OC= 5.11
Upper basin
Lower basin
10
N
W
E
S


Station 10
2.7
3.3
1.7
2.7
25.7
Eggerella scabra, 63.3
Eggerella scabra
Elphidium selseyense
Ammonia beccarii
Ammoscalaria runiana
Bulimina elongata
Bulimina marginata


Loch Creran
%OC= 4.62
Upper basin
Lower basin
11
N
W
E
S


Station 11
3.0
2.0
3.3
5.3
23.0
Eggerella scabra, 61.7
Eggerella scabra
Elphidium selseyense
Ammonia beccarii
Ammoscalaria runiana
Bulimina elongata
Bulimina marginata


Loch Creran
%OC= 1.90
Upper basin
Lower basin
12
N
W
E
S


Station 12
2.7
2.7
5.7
8.0
Ammonia beccarii, 28.3
21.7
21.7
Ammonia beccarii
Eggerella scabra
Ammoscalaria runiana
Elphidium selseyense
Bulimina marginata
Cibicides lobatulus
Textularia bocki

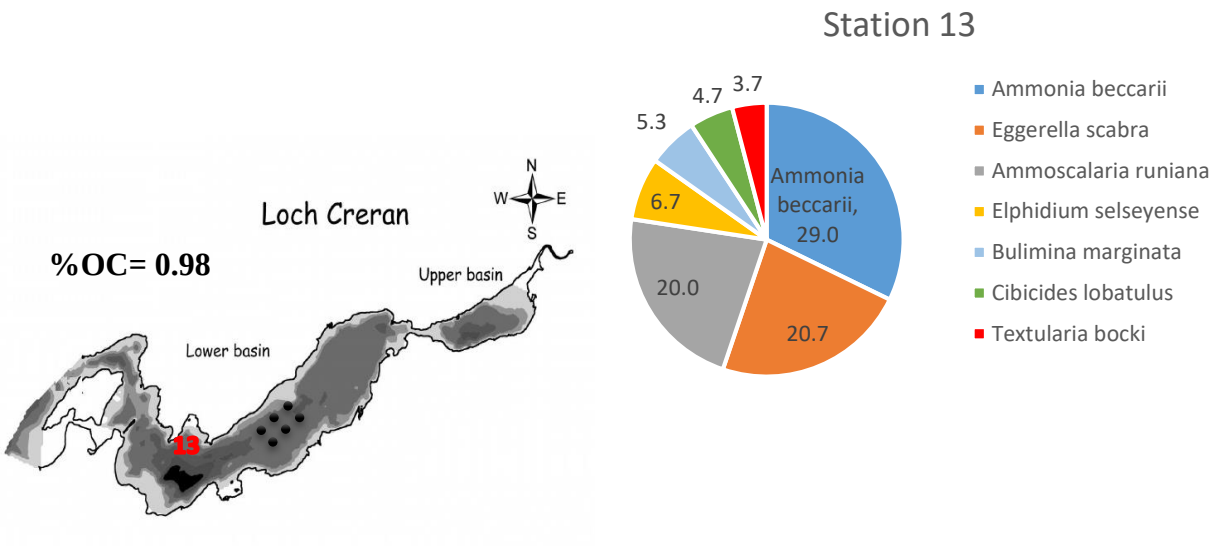


Figure 4. 2 Relative abundance (%) of the most common benthic foraminifera in the surface sedminets (0_1 cm) at each sampling station, Loch Creran.

4.5.2 Indicator species

In the present study, some species are frequent and very abundant in the surface sediment of Loch Creran. These species are generally continuously present in almost all surface samples and four indicator species of organic-rich sediments are recognized. The average relative abundances of these four species are greater than or equal to 5% throughout; they are *Ammonia beccarii*, *Eggerella scabra*, *Ammoscalaria runiana* and *Elphidium selseyense*. Table 4.4 illustrates the average relative abundance of each dominant species at the thirteen locations. These diagnostic species change their relative abundance with proximity to the impacted sites, suggesting that benthic foraminifera can be used as a bio-monitoring studies. A taxonomic description of these four key indicators is provided here in order to guide their future identification in similar, applied studies.

Table 4. 4 illustrates the relative abundance (%) of each indicator species at the thirteen locations.

Stations	*Eggerella scabra*	*Ammonia beccarii*	*Ammoscalaria runiana*	*Elphidium selseyense*
Station 01	16.9	28.8	7.7	2.4
Station 02	41.9	24.2	18.4	3.8
Station 03	37.6	23.8	21.1	3.9
Station 04	25.8	32.3	20.8	4.6
Station 05	21.3	34.0	18.0	4.7
Station 06	43.0	25.0	19.3	5.0
Station 07	25.0	30.0	18.3	7.3
Station 08	18.0	28.7	15.0	6.0
Station 09	64.3	3.3	2.3	24.0
Station 10	63.3	2.7	2.7	25.7
Station 11	61.7	5.3	3.3	23.0
Station 12	21.7	28.3	21.7	8.0
Station 13	20.7	29.0	20.0	6.7

***Ammonia beccarii* (Linné)**

Family ROTALLIDAE Ehrenberg, 1839
Genus AMMONIA Brunnich, 1772
Ammonia beccarii (Linné)

Description: (Figure 4.3)

Test is trochospirally, coiled biconvex, periphery sub-rounded, slightly lobate. The evolute spiral, dorsal side is gently convex, the involute ventral side more strongly so with a deep umbilical excavation and central umbilical plug. Chambers somewhat inflated, numbering 9 in the final whorl, tapering towards the umbilicus where they are irregular, bossed and tend to become digitate. Sutures distinct, deeply incised on the ventral side, radial, nearly straight; dorsal spiral suture distinct, deeply incised but tending to become thickened and nearly flush over earlier whorls; pits mark the location of the junction between radial & spiral sutures. Test wall translucent, highly perforate, fine. Aperture, an interio-marginal slit which extends into umbilical area and back words as long spiral suture.

In the present study *Ammonia beccarii* (Linné) is the most abundant benthic foraminiferal species of the total fauna in Loch Creran. This species was typically recorded in high percentages in the main basin; its average abundance is ranges from 23.8 – 34% of the total foraminiferal fauna. The average relative abundance for this species in the study area is plotted in

Figure 4.4. The figure illustrates that *Ammonia beccarii* has a high relative abundance in the main basin, specifically at the reference (control) site. The relative abundance of this species in the control samples ranges from 25.3 – 32%. Equally, station 05, which located away from the farming cages, represents the highest average relative abundance with 34%. However, this species is still found in the other samples, including the impacted sites, with relative abundances up to 32%.

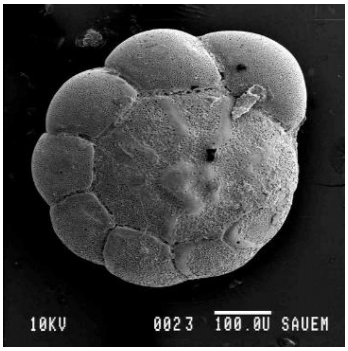


Figure 4. 3 *Ammonia beccarii* (Linné) "dorsal view", 100µm.

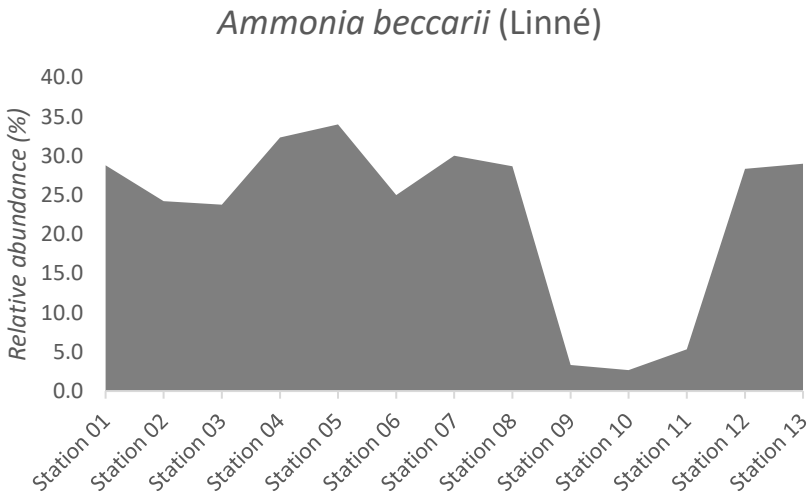


Figure 4. 4 Relative abundance (%) and distribution of *Ammonia beccarii* (Linné).

***Eggerella scabra* (Williamson)**

Family EGGERELLIDAE Cushman, 1937
Genus EGGERELLA Cushman, 1933
Eggerella scabra (Williamson)

Description: (Figure 4.5)

Test is elongate, the initial part of the test is trochospirally coiled and reduced to triserial in the adult part. Early portion with 4 to 5 chambers in a whorl, later portion triserial, and increase rapidly in size so that the last whorl commonly forms half the length of the test. Wall is typically agglutinated with larger grains; normally 4 to 5 whorls; chambers numerous, low and broad in early portion, increasing slowly in relative height as added, normally three chambers in final whorl, very inflated and extending outwards of the axis of the test, giving the test a triangular outline in aperture view and an almost flat aperture face; sides straight, except for sutures, increasing at 25° from the axis; sutures distinct and depressed; aperture small, central, low arch at base of final chamber, sometimes with a narrow lip.

Eggerella scabra (Williamson) is the second most abundant species in the studied samples from Loch Creran. Its average relative abundance ranges from 16.9 – 64.3% of the total foraminiferal fauna. Figure 4.6 plots the average relative abundant and the geographical distribution of *Eggerella scabra* in the studied area. The highest relative abundance was recorded in the

upper basin stations (e.g. samples GB-03-C, GB-07-A and GB-09-A) ranging from 61.7 – 64.3%. In addition, this species was present in high abundance beneath fish farming sites (e.g. stations 02, 03 and 06) with average abundance of 41.9%, 37.6% and 43%, respectively. Conversely, the lowest abundance of this species was recorded at the control site (station 01) and recorded to be 16.9%. Although the relative abundance at the remaining sample locations was low compared to the impacted stations, this species still shows an obvious distribution in stations away from farming sites.

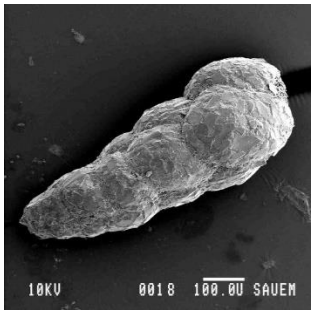


Figure 4. 5 *Eggerella scabra* (Williamson), 100µm.

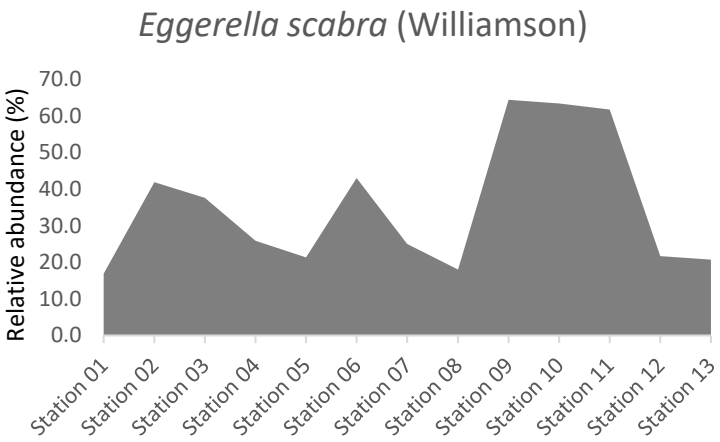


Figure 4. 6 Relative abundance (%) and distribution of *Eggerella scabra* (Williamson).

***Ammoscalaria runiana* (Heron-Allen and Earland)**

Family DISCAMMINIDAE Mikhalevich, 1980
Genus AMMOSCALARIA Hö̈glund, 1947
Ammoscalaria runiana (Heron-Allen & Earland)

Description: (Figure 4.7)

The test is planispiral, flattened and shows no obvious external evidence of the chambers which are separated by thin organic membranes. Marginal edge very irregular, thick and rounded. Test wall coarsely agglutinated with angular sand grains. Little fine matrix, moderately cemented. The position and shape of the aperture is variable and sometimes not observed but reported to be a protruding oval opening in the aperture face with lip.

Ammoscalaria runiana (Heron-Allen and Earland) is the third most abundant benthic foraminifera of in the studied samples. Its average relative abundance ranges from 2.7%, recorded in the upper basin samples, to 21.7% recorded in the main basin regions. Figure 4.8 demonstrates the relative abundance and the distribution of this species according to sampling stations. Although the relative abundance of *Ammoscalaria runiana* is less compared to *Eggerella scabra,* it is distributed in almost all the stations. Stations 02, 03 and 06 show a relative abundance of 18.3 – 21.1% and all the impacted sites

are represented by this species. However, the bathymetrical distribution of *Ammoscalaria runiana* is more typically associated with the un-impacted stations of Loch Creran.

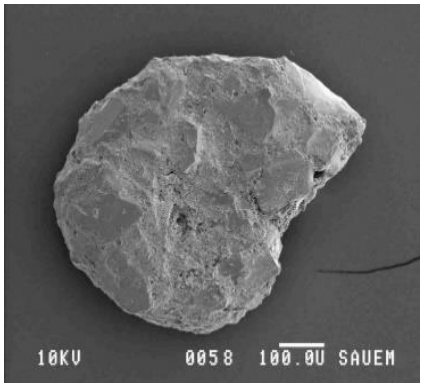


Figure 4. 7 *Ammoscalaria runiana* (Heron-Allen and Earland) "side view", 100µm.

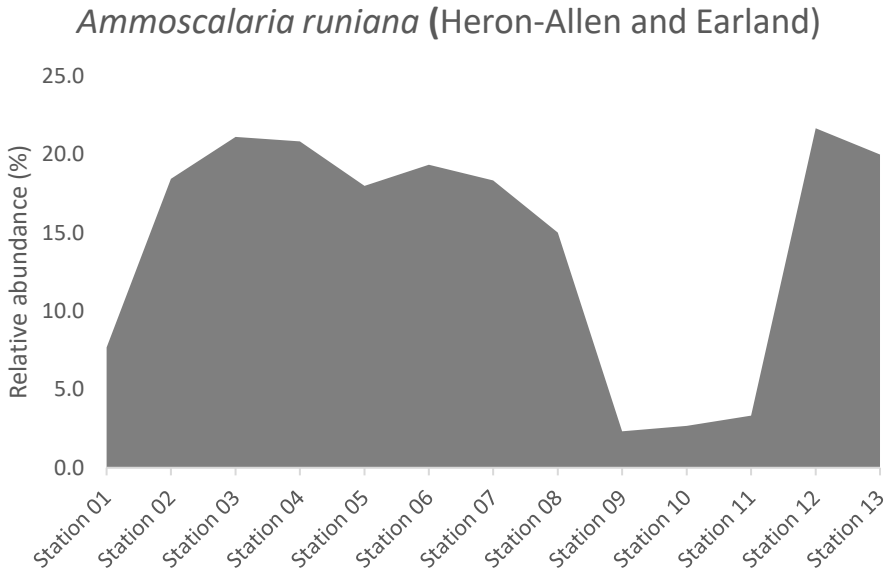


Figure 4. 8 Relative abundance (%) and distribution of *Ammoscalaria runiana* (Heron-Allen and Earland).

***Elphidium selseyense* (Heron-Allen & Earland)**

Family ELPHIDIIDE Galloway, 1933
Genus ELPHIDIUM de Montfort, 1808
Elphidium selseyense (Heron-Allen & Earland)

Description: (Figure 4.9)

Test medium, planispiral, involute and moderately compressed. Periphery rounded, slightly lobate, with 8 chambers visible in the final whorl. Chambers increasing in size steadily. Sutures distinct, gently curving backwards towards the periphery, incised. Numerous papillae fill the generally open sutures, particularly where they connect with the excavated umbilicus. Septal bridges vary in number as do the deeply excavated septal pits. Aperture comprises a single row of pores along the base of the apertural face. Test wall translucent and densely perforate, giving a distinctly hazy appearance to this form.

Elphidium selseyense (Heron-Allen & Earland) is the fourth most abundant species of the foraminiferal fauna found in areas surrounding Loch Creran. The bathymetrical distribution of *Elphidium selseyense* is more concentrated and occupies the impacted stations of Loch Creran, specifically in the upper basin. For example, at stations 09, 10 and 11, the average relative abundances tend to be the highest and were recorded as 24%, 25.7% and 23%,

respectively. Figure 4.10 illustrates the relative abundance and the distribution of this species according to sampling stations. Elsewhere, the relative abundances of this species are low, ranging from 2.4% at station 01 to 8% at station 12.

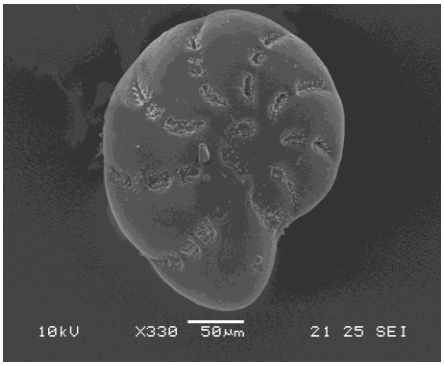


Figure 4. 9 *Elphidium selseyense* (Heron-Allen & Earland) "side view", 50 µm.

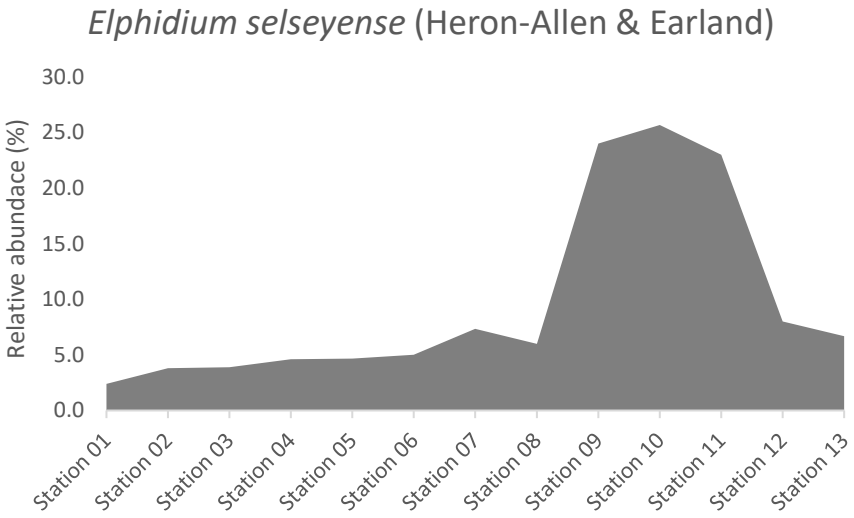


Figure 4. 10 The relative abundance (%) and distribution of *Elphidium selseyense* (Heron-Allen & Earland).

4.5.3 Species diversity

The values of the two (Fisher alpha and Shannon-Weaver) diversity indices are listed in Table 4.5 for all the surface samples. Figure 4.11 and 4.12 illustrate the two diversity indices for benthic foraminifera across all stations. It is very clear from the two figures that the diversity in the main and upper basin samples varies significantly. The analysis provides evidence that foraminiferal diversity is related to areas under high organic matter (OM) influence. The diversity (either Fisher-α or Shannon-Weaver values) seems to be highest at the reference (control) station (e.g. samples CC-01-A, CC-01-B and CC-01-C) ranging from 6.8 – 8.2, whilst in the upper basin (e.g. samples GB-03-C, GB-07-A and GB-09-A) and at the fish farm stations (e.g. samples CC-02-A, CC-02-B, SC-02-A, CC-03-A, CC-03-B, CC-03-C and SC-06-A), the diversity indices are at their lowest ranging from 1.2 – 1.9 and 2.2 – 3.9, respectively. Away from farming sites (e.g. SC-04-A, SC-04-B, SC-05, SC-07-A, SC-08-A, GB-20-A and GB-28-A), the samples tend to have slightly lower diversity indices (ranging from 4.2 – 8.2) in comparison with the reference (control) site, but diversity is higher than that beneath the fish farming cages.

Table 4. 5 Benthic foraminiferal diversity indices and environmental parameters from the Loch Creran sampling stations.

Sample ID code	*Latitude, N*	*Longitude, W*	*Depth [m]*	*BWT °C*	*% OM*	*% Clay*	*% Silt*	*% Sand*	*Shannon_H*	*Fisher_alpha*
CC-01-A	56° 31.141	5° 22.386	37.00	12.60	2.85	20.70	46.40	32.80	2.78	10.27
CC-01-B	56° 31.134	5° 22.299	37.00	12.60	2.31	20.00	44.70	35.00	2.57	8.68
CC-01-C	56° 31.133	5° 22.298	38.00	12.60	2.18	19.00	43.10	37.70	2.42	6.83
CC-02-A	56° 31.372	5° 21.434	29.90	12.00	3.50	17.60	43.50	38.70	1.66	3.32
CC-02-B	56° 31.372	5° 21.437	30.00	12.00	3.74	16.50	44.60	38.80	1.53	2.50
SC-02-A	56° 31.373	5° 21.436	27.20	12.00	3.94	18.40	45.00	36.50	1.60	2.76
CC-03-A	56° 31.376	5° 21.465	29.20	11.70	2.59	13.00	42.00	44.90	1.73	3.32
CC-03-B	56° 31.375	5° 21.464	29.00	11.70	2.32	13.60	41.60	44.80	1.74	3.90
CC-03-C	56° 31.375	5° 21.464	29.00	11.70	2.79	13.70	42.30	43.80	1.67	3.32
SC-04-A	56° 31.368	5° 21.475	29.80	11.20	2.87	14.30	42.60	42.80	1.83	4.20
SC-04-B	56° 31.370	5° 21.478	29.70	11.20	2.32	14.50	42.70	42.80	1.89	5.80
SC-05-A	56° 31.359	5° 21.565	30.10	11.90	1.90	19.20	49.50	31.20	2.00	5.46
SC-06-A	56° 31.486	5° 21.167	27.40	12.10	4.46	15.10	47.00	37.70	1.50	2.24
SC-07-A	56° 31.483	5° 21.147	24.80	11.40	2.69	16.90	52.90	30.10	1.93	4.82
SC-08-A	56° 31.520	5° 21.065	23.00	10.80	1.66	16.10	57.70	26.10	2.39	8.29
GB-03-C	56° 33.188	5° 15.130	12.50	-	4.18	7.35	86.40	6.10	1.07	1.51
GB-07-A	56° 33.010	5° 15.072	13.72	-	5.11	7.55	86.00	6.30	1.04	1.28
GB-09-A	56° 32.937	5° 15.549	22.70	-	4.62	8.84	86.90	4.10	1.18	1.99
GB-20-A	56° 31.430	5° 20.220	17.60	-	1.89	8.32	72.00	19.60	2.04	4.51
GB-28-A	56° 31.293	5° 22.694	29.60	-	0.98	6.22	48.70	45.00	2.11	6.13

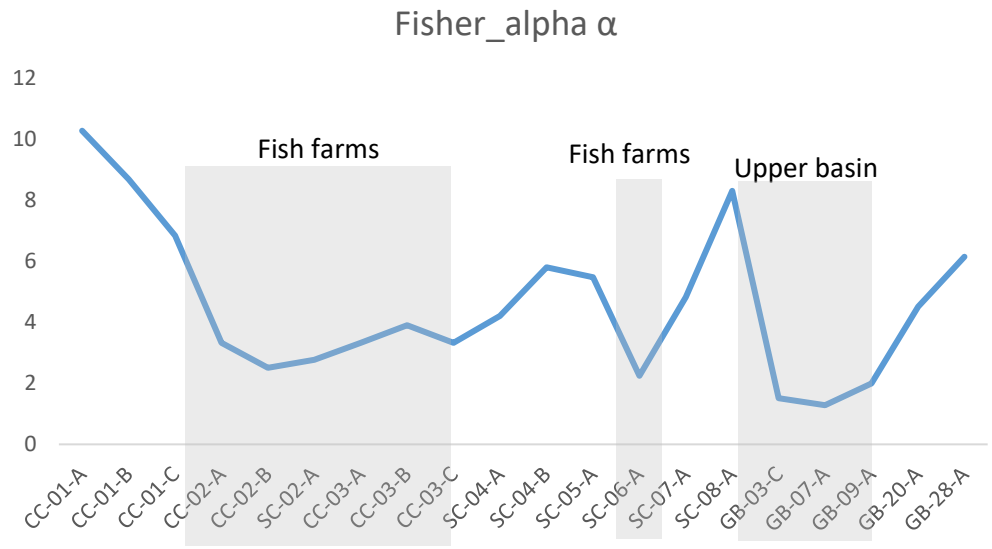


Figure 4. 11 Fisher alpha α index for benthic foraminifera, Loch Creran surface sampling stations.

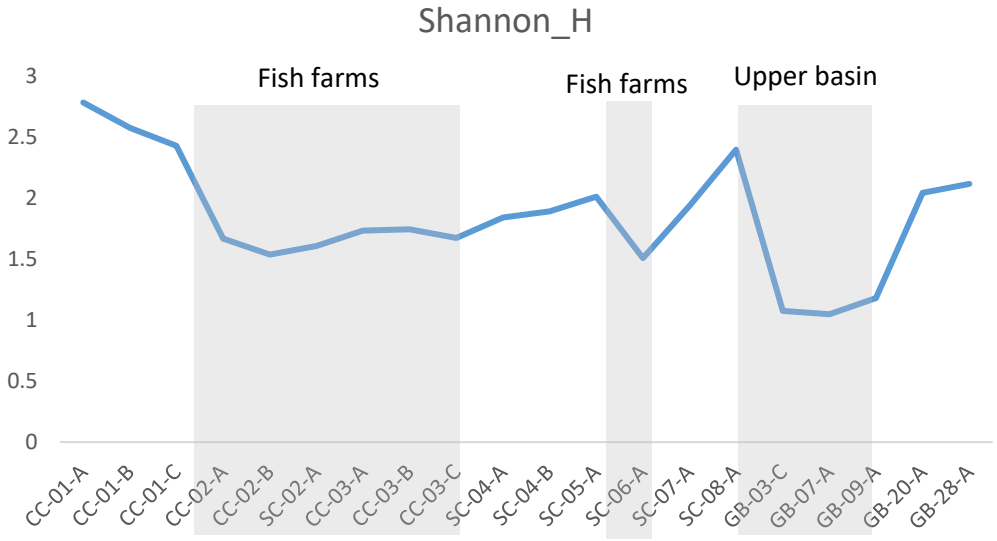


Figure 4. 12 Shannon_H diversity index for benthic foraminifera, Loch Creran surface sampling stations.

4.5.4 Benthic foraminiferal assemblages

4.5.4.1 Cluster analysis (CA)

The relationship among foraminiferal assemblages in association with environmental parameters (temperature, salinity, pH, and the DO_2), grain size analysis and the organic matter (OM) contents data are studied in an attempt to identify indicators of adaptability to environmental stress. In particular, concentrations of the OM contents in the surficial sediment are investigated to assess environmental pollution levels that are further linked to regions with extremely low dissolved oxygen concentration (DO_2).

Cluster analysis (CA) was run on the twenty surface samples to determine the distribution and relationship of the dominant foraminifera in Loch Creran. The CA is one of the most widely applied multivariate analytical techniques used to classify entities (e.g. samples, species, physical measurements) into similar groups or clusters and to quantify the relationships between groups and serve to simplify or condense the complicated structure of multivariate data which makes exploration of relationships easier (Parker and Arnold, 1999). In this study, the CA analysis identified four broad benthic assemblage groups (Figure 4.13). Separation between the groups is mainly due to different responses to OM enrichment. Each group is characterized by

similar benthic foraminiferal assemblages and environmental variables. Furthermore, to validate the cluster analysis assemblages results, non-metric Multi Dimensional Scaling (MDS) using PAST (Hammer et al., 2001) was applied on the benthic foraminifera abundance data. The results of the MDS shows that assemblage groups created by CA are replicated in MDS space, hence can be considered as significant assemblages (Figure 4.14). The main basin area of Loch Creran appears to be clustered into three groups, (i) A1, (ii) A2-1 and (iii) A2-2. Group A1 primarily consist of the samples collected from the reference (control) sites. Group A2-1 represents samples collected at a distance from the farming cages namely the non-fish farming assemblages. The third group (A2-2), the fish-farming assemblage, contains samples collected directly beneath the fish farming sites. Significantly, the CA places the upper basin (the fourth group) in a separated assemblage group; these samples have the lowest species diversity, suggesting that environment is stressed. All sampling station assemblages were dominated by two indicator species *Ammonia beccarii* and *Eggerella scabra,* with notable differences in their proportions in each assemblage group. At the un-impacted sampling stations, *A. beccarii* dominated the assemblages and comprised more than 70% of the total assemblages. Conversely, *E. scabra* become more important at the impacted sites (beneath fish farming cages and river influenced regions

where OM inputs are greatest), exhibiting the second highest abundance with more than 60% of the total assemblages. Additionally, in the upper basin, *Elphidium selseyense* were found to be equally dominant with *E. scabra*. The most abundant taxa for each sample in the 4 assemblage groups are listed in Table 4.6.

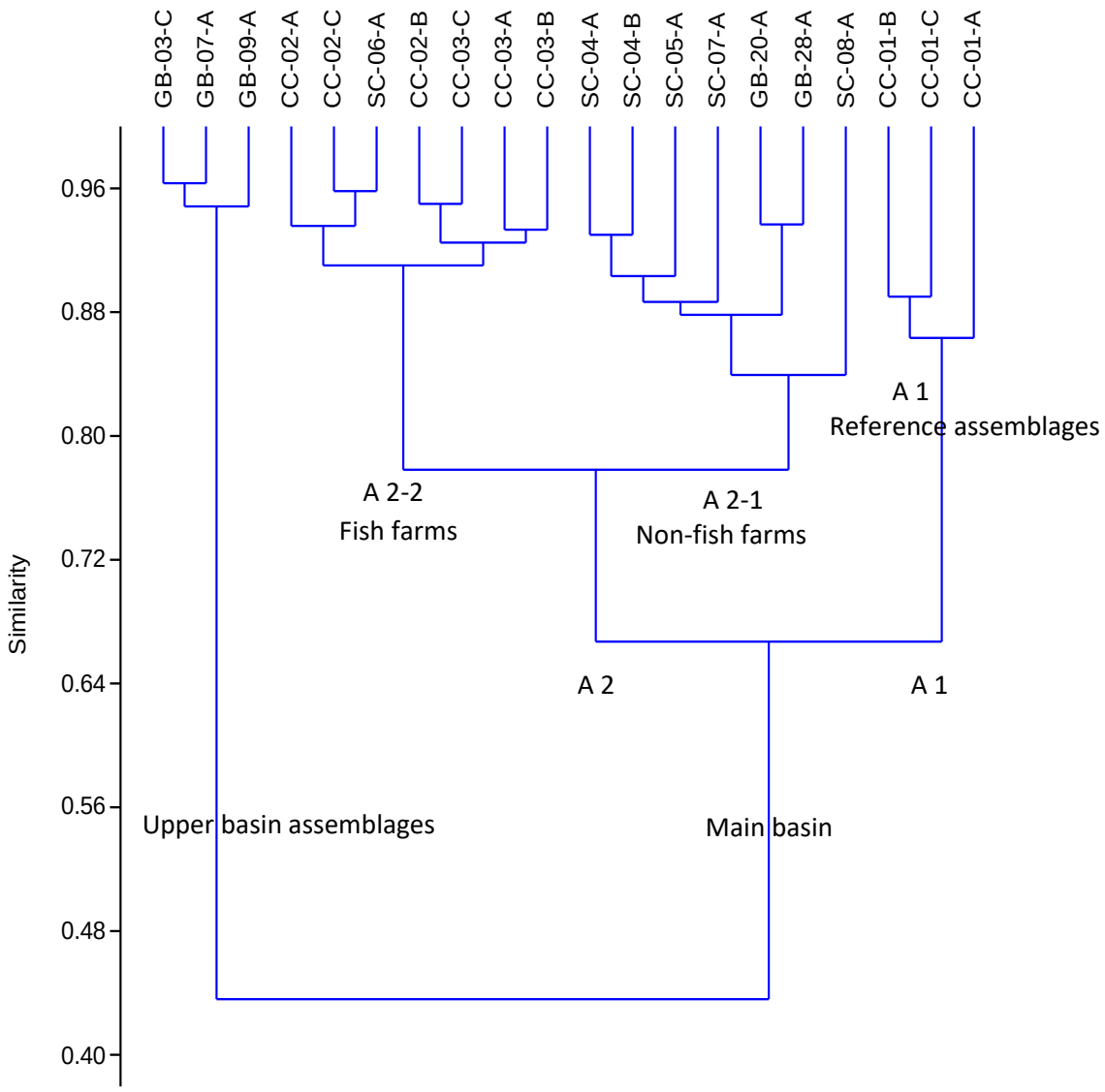


Figure 4. 13 The cluster analyses of Loch Creran modern benthic foraminifera using PAST (Hammer et al., 2001) in order to determine foraminiferal assemblages. The cluster analysis identifies 4 assemblage groups, grouped with similarities. Assemblage groups are: (i) Reference assemblage group; (ii) non-fish farming assemblage groups; (iii) fish farming assemblage groups and (iv) the upper basin assemblage groups.

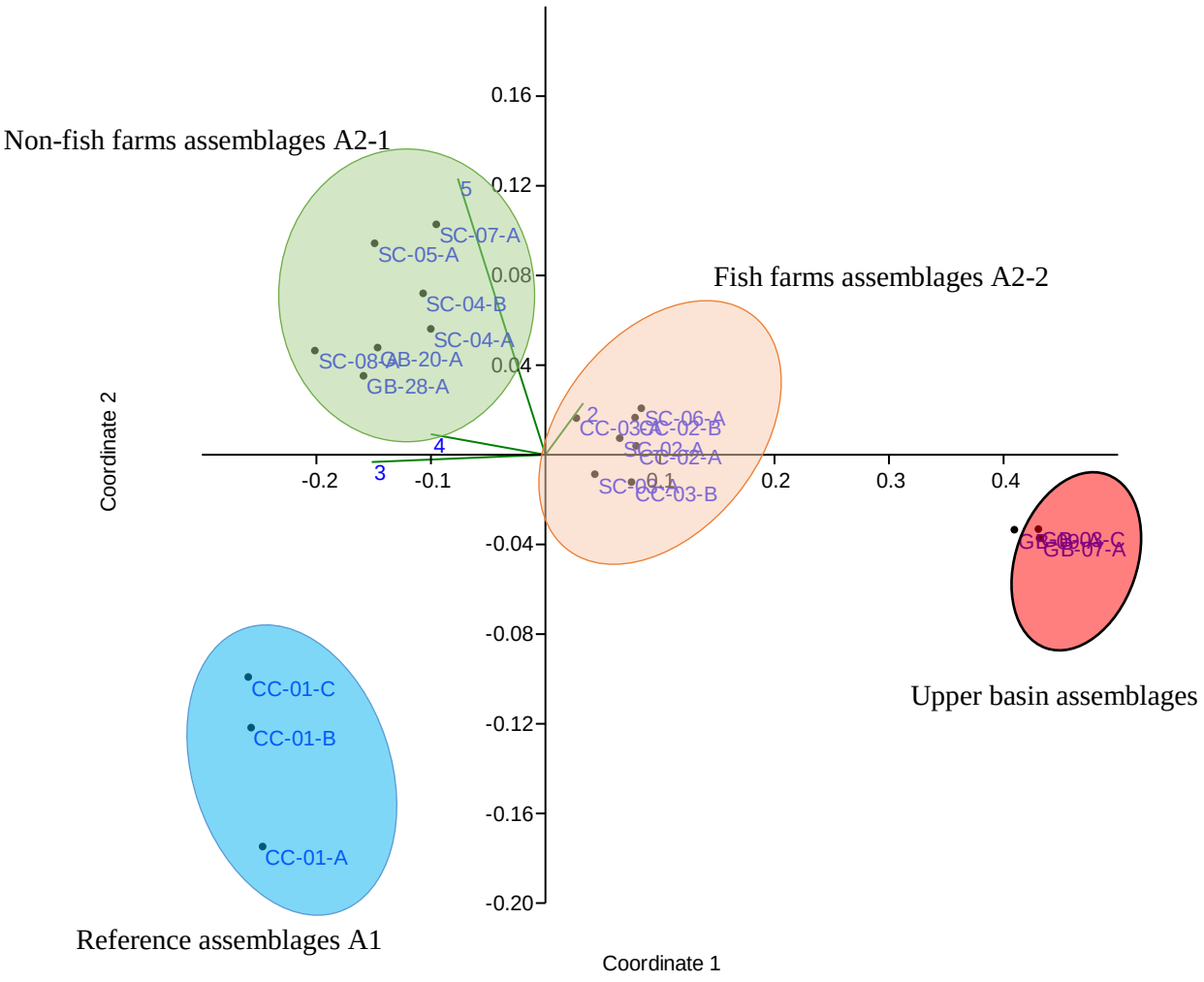


Figure 4. 14 Validation of the cluster analysis (CA) via non-metric Multi-Dimensional Scaling (MDS), using PAST (Hammer et al., 2001), shows that assemblage groups defined by the cluster analysis are replicated in MDS space, hence can be considered as significant assemblages.

Figure 4. 6 The most abundant taxa for each sample in the 4 assemblage groups.

		CC-01-A		CC-01-B		CC-01-C
Group A 1	**Species**	%	**Species**	%	**Species**	%
	Ammonia beccarii	25.3	Ammonia beccarii	29	Ammonia beccarii	32
	Eggerella scabra	15	Eggerella scabra	18	Eggerella scabra	17.7
	Ammoscalaria runiana	10	Ammoscalaria runiana	6.3	Ammoscalaria runiana	6.7
	Asterigerinata mamilla	5.7	Asterigerinata mamilla	6.7	Asterigerinata mamilla	6
	Textularia bocki	4	Textularia bocki	4.3	Textularia bocki	5.7
	Cibicides lobatulus	4	Cibicides lobatulus	5	Cibicides lobatulus	4.3

Group A 2-2		**CC-02-A**		**CC-02-B**		**SC-02-C**
	Species	%	**Species**	%	**Species**	%
	Eggerella scabra	41	***Eggerella scabra***	41.3	***Eggerella scabra***	43.3
	Ammonia beccarii	25.7	***Ammonia beccarii***	23.7	***Ammonia beccarii***	23.3
	Ammoscalaria runiana	16.7	***Ammoscalaria runiana***	22	***Ammoscalaria runiana***	16.7
	Bulimina marginata	5	***Bulimina marginata***	4	***Bulimina marginata***	5
	Elphidium selseyense	3	***Elphidium selseyense***	3.3	***Elphidium selseyense***	5.3
	Reophax scotti	1.7	***Reophax scotti***	2.7	***Reophax scotti***	1.3
		CC-03-A		**CC-03-B**		**CC-03-C**
	Species	%	**Species**	%	**Species**	%
	Eggerella scabra	37.3	***Eggerella scabra***	34.3	***Eggerella scabra***	41
	Ammonia beccarii	24	***Ammonia beccarii***	25	***Ammonia beccarii***	22.3
	Ammoscalaria runiana	20.7	***Ammoscalaria runiana***	21.7	***Ammoscalaria runiana***	21
	Elphidium selseyense	3.3	***Elphidium selseyense***	4.7	***Elphidium selseyense***	3.7
	Bulimina marginata	3.7	***Bulimina marginata***	5	***Bulimina marginata***	2.7
	Reophax scotti	1	***Reophax scotti***	1	***Reophax scotti***	2

	SC-06A
Species	%
Eggerella scabra	43
Ammonia beccarii	25
Ammoscalaria runiana	19.3
Elphidium selseyense	5
Bulimina marginata	4.7
Haplophragmoidesb bradyi	1

Continued (Table 4.6)

Group A2-1		**SC-04-A**		**SC-04-B**		**SC-05-A**
	Species	%	**Species**	%	**Species**	%
	Ammonia beccarii	31.3	***Ammonia beccarii***	33.3	***Ammonia beccarii***	34
	Eggerella scabra	26.7	***Eggerella scabra***	25	***Eggerella scabra***	21.3
	Ammoscalaria runiana	21.7	***Ammoscalaria runiana***	20	***Ammoscalaria runiana***	18
	Elphidium selseyense	4	***Elphidium selseyense***	5.3	***Bulimina marginata***	7
	Bulimina marginata	5.3	***Bulimina marginata***	5	***Elphidium selseyense***	4.7
	Bulimina elongata	1	***Bulimina elongata***	1.7	***Asterigerinata mamilla***	1.7
	Asterigerinata mamilla	1	***Asterigerinata mamilla***	1.7		
		SC-07-A		**GB-20-A**		**GB-28-A**
	Species	%	**Species**	%	**Species**	%
	Ammonia beccarii	30	***Ammonia beccarii***	28.3	***Ammonia beccarii***	29
	Eggerella scabra	25	***Eggerella scabra***	21.7	***Eggerella scabra***	20.7
	Ammoscalaria runiana	18.3	***Ammoscalaria runiana***	21.7	***Ammoscalaria runiana***	20
	Bulimina marginata	7.7	***Elphidium selseyense***	8	***Elphidium selseyense***	6.7
	Elphidium selseyense	7.3	***Bulimina marginata***	5.7	***Bulimina marginata***	5.3
	Asterigerinata mamilla	1.7	***Cibicides lobatulus***	2.7	***Cibicides lobatulus***	4.7
			Textularia bocki	2.7	***Textularia bocki***	3.7

Upper		**GB-03-C**		**GB-07-A**		**GB-09-A**
basin	**Species**	%	**Species**	%	**Species**	%
	Eggerella scabra	64.3	***Eggerella scabra***	63.3	***Eggerella scabra***	61.7
	Elphidium selseyense	24	***Elphidium selseyense***	25.7	***Elphidium selseyense***	23
	Ammonia beccarii	3.3	***Ammonia beccarii***	2.7	***Ammonia beccarii***	5.3
	Ammoscalaria runiana	2.3	***Ammoscalaria runiana***	2.7	***Ammoscalaria runiana***	3.3
	Bulimina elongata	2.7	***Bulimina elongata***	3.3	***Bulimina elongata***	3
	Bulimina marginata	1.3	***Bulimina marginata***	1.7	***Bulimina marginata***	2

4.5.4.2 Reference assemblage group (Group A1)

Samples from this assemblage group lie mainly in the main basin of Loch Creran, representing the reference (control) station as a distinct assemblage type. The samples in this group are dominated by *A. beccarii* and typically have the highest abundance among all species in this group ranging between 25 – 32 % (table 4.6). The assemblage also contains significant abundances (i.e. >4%) of secondary diagnostic species, which include *E.scabra* (15 – 18%), *A. runiana* (6 – 10%), *A. mamilla* (5.7 – 6%), *T. bocki* (4 – 5.7%) and *C. lobatulus* (<5%). Additionally, some other species are common in the reference(control) samples with abundances often > 3%, such as *Bulimina marginata*, *Bulimina elongate*, *Elphidium aculeatum*, *Nonionella turgida* and *Elphidium selseyense* (Figure 4.15).

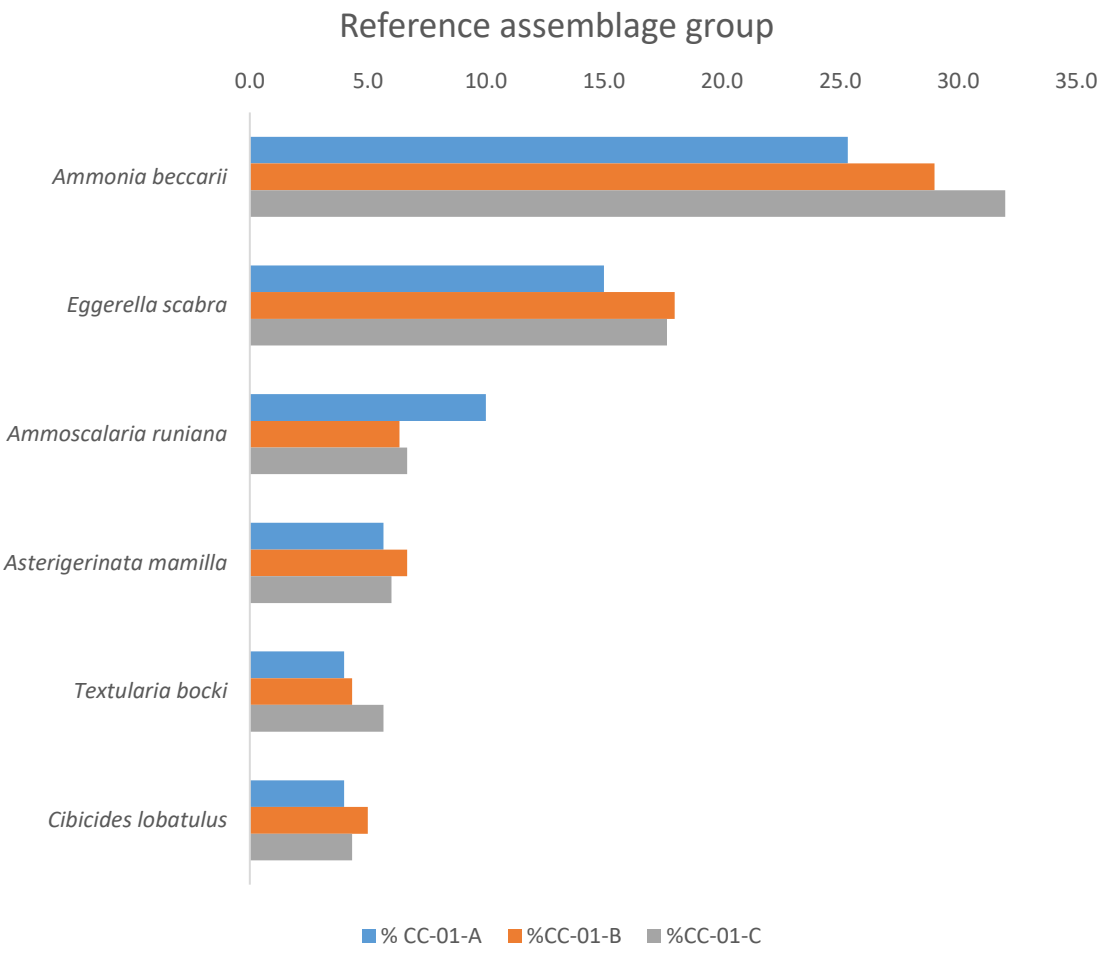


Figure 4. 15 The most abundance data (%) of the dominant foraminifera for the reference assemblage.

4.5.4.3 Non-fish farming assemblage group (Group A2-1)

The majority of the samples of this assemblage group (i.e. SC-04-A, SC-04-B, SC-05-A, SC-07-A, SC-08-A, GB-20-A and GB-28-A) lie in the main basin and were collected at a distance from farming sites, where sediment OM content is lower. The assemblage is dominated by *A.beccarii* with high abundance (30 – 34 %). Additionally, other common species in these samples include *E. scabra* (21 – 26%), *A. runiana* (18 – 21%), *B. marginata* (5 – 7.7%) and *E. selseyense* (4 – 7.3%). The samples of this assemblage group contain species number of ranging between 15 to 31, indicating a relatively high species richness. Thus, we can assume that the samples representing these stations (away from farming sites) largely un-impacted by OM inputs to the benthic environment (Figure 4.16).

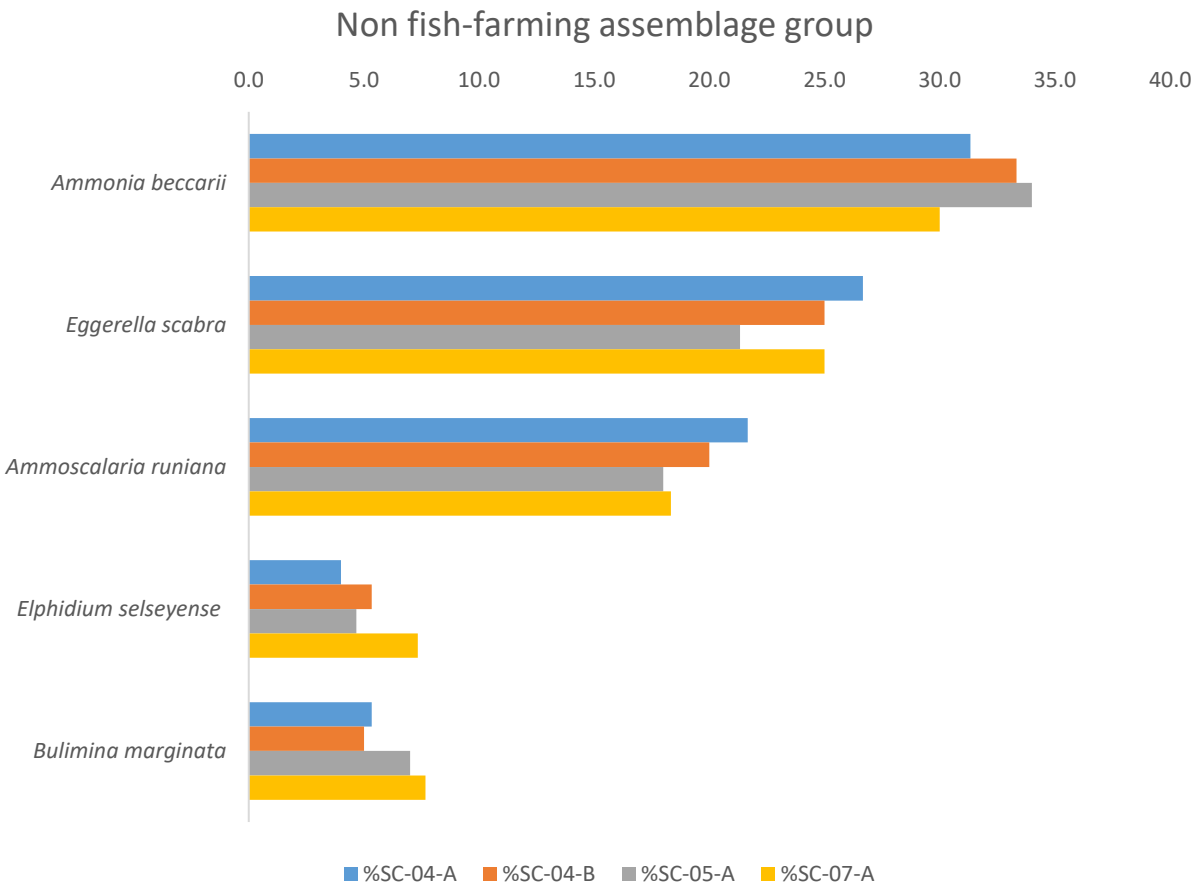


Figure 4. 16 Abundance data (%) of the dominant foraminifera for the non-fish farming assemblage.

4.5.4.4 Fish-farms assemblage group (Group A2-2)

This assemblage group comprises mainly the fish farms samples which appears to have been impacted by OM loading of the sediments (CC-02-A, CC-02-B, SC-02-A, CC-3-A, CC-03-B, CC-03-C and SC-06-A). The samples have some of corroded and broken specimens, and this properly due to lowering of the pore-water pH from decaying OM resulting from the overlying fish farm activities. The most dominated species in all samples of this assemblage group is *E. scabra*. It appears to be an important species since it presents itself in the highest abundance in all the samples. We can conclude this species could be utilised as an indicator of stressed environment since it can tolerate high concentration of the OM is sediments beneath fish farming sites. The average abundance of *E. scabra* is more than 40%. Other tolerant species in this assemblage are *A. beccarii*, *A. runiana*, *B. marginata*, *E. selseyense* and *R. scotti* which have an average abundance of 24%, 19%, 4.3%, 4% and 1.4%, respectively (Figure 4.17).

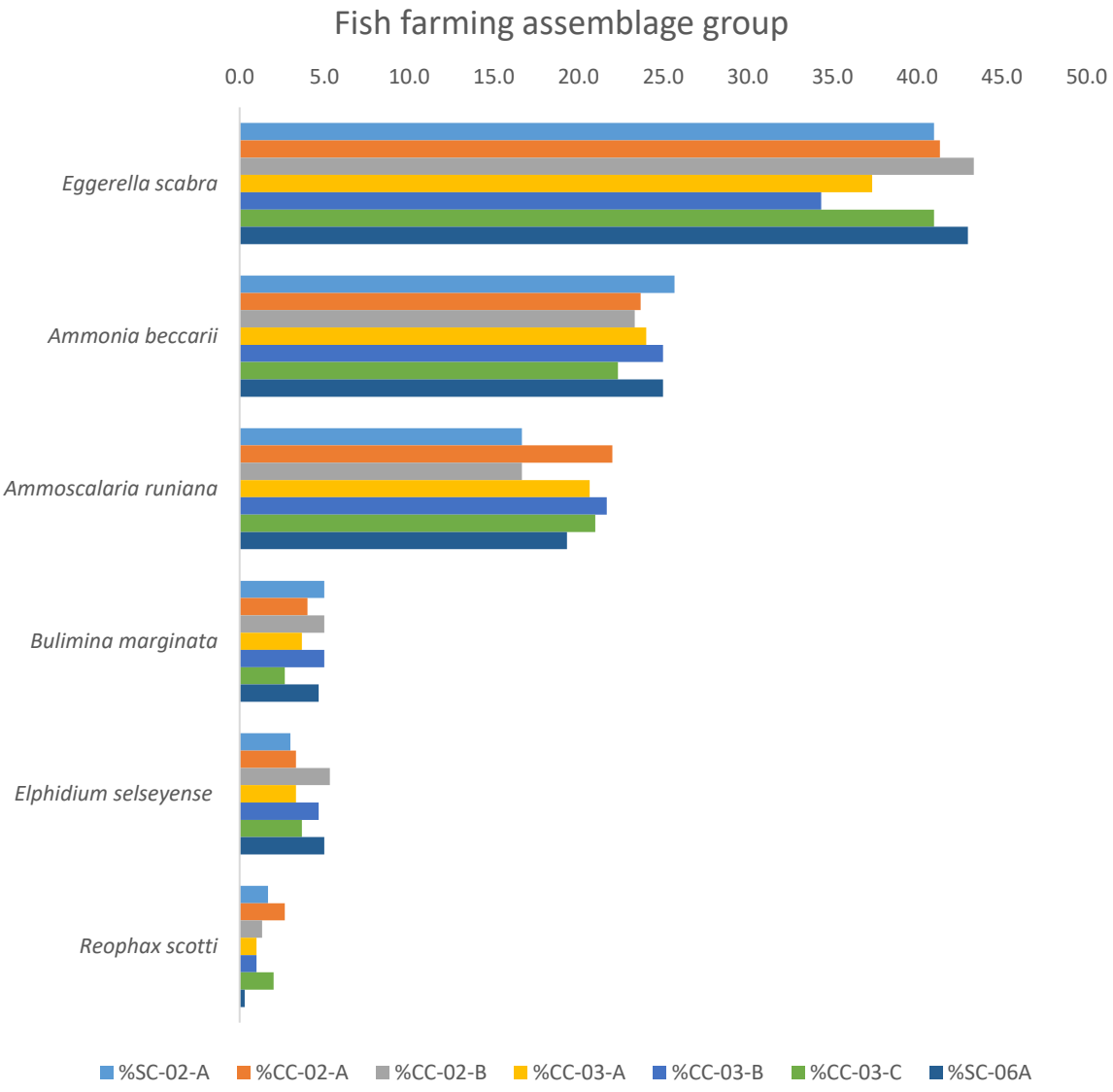


Figure 4. 17 Abundance data (%) of the dominant foraminifera for the fish-farming assemblage group.

4.5.4.5 Upper basin group (River influence assemblages)

This assemblage group primarily consists of the upper basin samples (e.g. samples GB-03-C, GB-07-A and GB-09-A). The assemblage group contains high proportions of agglutinated taxa and is typically dominated by *E. scabra* with abundances of 61- 64 %. It is interesting to note that *E. selseyense* is the second most abundance species (23 – 25%) in this assemblage group. The cluster analysis places the upper basin in one group, most properly due to the high abundances of these two species, which appear to tolerate the high percentage of the organic matter (OM) enrichment and potentially lower salinity of the upper basin (Figure 4.18).

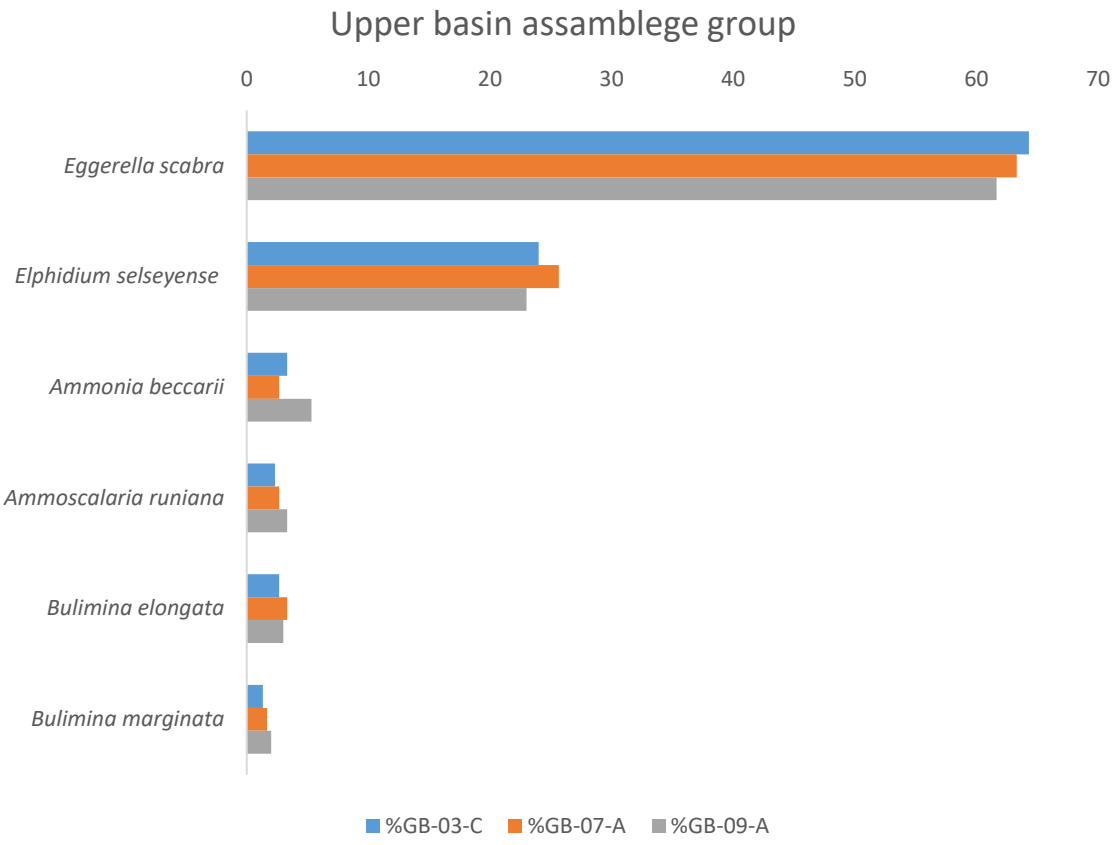


Figure 4. 18 Abundance data (%) of the dominant foraminifera for the upper basin assemblage group.

4.6 Discussion

This study evaluated the applicability of utilising benthic foraminifera as a bio-monitoring tool to assess the environmental impacts of organic matter (OM) from different sources (e.g. fish farms and river influence). Since benthic foraminifera can provide environmental information from stressed environments through their overall assemblage composition (Murray, 1991), the data generated from their spatial distribution pattern together with a range of environmental variables in the studied area confirm that the foraminiferal community composition are very promising and can be used as an indicator of organic matter enrichment.

According to the results obtained, the upper basin assemblages typically have much lower foraminiferal abundances compared to the main basin assemblages. Similarly, samples from upper basin seem to have significantly higher organic matter (OM) contamination than all other sampling sites. Hence, the high accumulation of the organic matter (OM) in these sediments will lead to a decline in foraminiferal abundance and diversity in those zones. Eventually, this could result in an anoxic environment which in turn will create a stressful environment and will cause extremely low foraminiferal abundances (Bolyovskoy & Wright, 1976). Several studies obtained the same results and proved that excessive exposure to organic

matter (OM) waste can have large effects on benthic community structure (Kutti et al. 2007; Hargrave 2010; Neofitou et al. 2010). Other studies have shown that variations in foraminiferal communities (e.g., Alve, 1991, 1995; Culver and Buzas, 1995; Martin 2000; Scott et al., 2001; Cearreta et al., 2002) in combination with certain environmental parameters (e.g. sediment grain-size, water dissolved oxygen and organic matter contents) can be used as an indicator of environmental stress (Thornton and McManus, 1994; Maksymowska et al., 2000; Corbett et al., 2006).

It was noted that some taxa were exhibited low abundances in the impacted sites, and this confirms the hypothesis that some species are sensitive to organic matter contents and needs to expend a considerable energy to survive these harsh environments. The porcelaneous taxa, for example, were noted to be almost entirely or present in only very low percentages in fjordic environments (Alve & Nage, 1990; Murray et al., 2003). This may explain the general absence of this wall type in the upper basin (River Creran) samples. However, other species were dominated the un-impacted environment, for example *A.becarri*. This species is (very) sensitive to organic enrichment, and mainly occur in natural unpolluted environment. This species is prominent at the reference site(s), where natural conditions are found, characterised by low OM contents. It showed a clear decrease (ideally in

absolute as well as relative abundance) in case of increasing organic enrichment. The restricted regions were dominated by agglutinated taxa (e.g. *E. scabra* in this study). *E. scarbra* species was shown by its abundance increase towards more organic enriched areas. However, the density maximum of *E.scabra* is usually fairly decrease at areas of minimum organic enrichment. Murray et al., (2003) reported similar results of the dominance of the agglutinated taxa assemblage at stressed environment on the organic-rich surface sediments of Loch Etive. The high abundance of agglutinated taxa may be interpreted and explained by their 'tolerant' and ability to survive under stressed environments and confirms that they can tolerate the environmental pressures caused by the organic matter (OM) load (e.g., Grall and Glémarec, 1997; Alve et al., 2016).

Comparison of benthic foraminiferal abundances from the upper basin with those from the main basin environments varies greatly depending on samples location. Samples which were located away from the farming sites yield much richer benthic foraminiferal abundances in comparison with the river influence environments (the upper basin). The highest foraminiferal abundances occur in the main basin samples collected from the reference (control) station. These samples have significantly higher foraminiferal diversity (both Fisher α and Shannon) and low organic matter (OM)

concentration. Thus, we can confirm that the gradual and steady trend of increasing foraminiferal abundance is closely tied to the decrease of the organic matter (OM) content of these sediments. (Scott et al., 2003).

4.7 Conclusion

The expected increase in fish farming related activities along the west coast of Scotland (and elsewhere in the world) will very likely result in increased releases of contaminants (i.e. organic matter) into the marine environment. To assess the environmental impacts of these activities on the benthic habitat, site specific and promising bio-monitoring tools are needed. In this study, a baseline data set of the spatial distribution pattern of benthic foraminifera was established in the Loch Creran region on the west coast of Scotland. A general distribution pattern of benthic foraminifera was documented and the relationship between foraminiferal associations and environmental variables was identified.

According to the analytical results, organic matter (OM) content and water dissolved oxygen (DO_2) both were the two main factors which played a considerable role in shaping and controlling the spatial distribution of modern benthic foraminifera in the study area. Overall, benthic foraminiferal population diversity and density were lowest at areas of high OM waste inputs

(i.e. fish farms and the river influences). We can conclude that high OM contamination induced a low diversity assemblage consisting of a few opportunistic species. Many scientists have investigated the effect of oxygen deficient and OM enrichment environment on benthic foraminiferal communities and reported the same conclusion which resulted in decreasing of various foraminiferal groups (Phleger and Soutar 1973; Hornung et al., 1989; Alve, 1991; Alve and Bernhard 1995; Bernhard et al. 1997; Bernhard and Bowser 1999).

Cluster analysis (CA) and Multi Dimensional Scaling (MDS) have been applied to classify the spatially distributed modern benthic foraminiferal assemblages of Loch Creran. Four benthic foraminiferal assemblages have been identified in the studied area, reflecting: i) a restricted or stressed environment (found in the upper basin); ii) fish farming assemblage groups; iii)) an unimpacted environment (at a control site; and iv) the non-fish farming assemblage groups (found at areas away from farming cages). The benthic foraminifera recorded in Loch Creran provide a distinct distribution pattern which potentially reflect the level of organic matter contamination within a stressed environment. Species diversity and abundance are typically higher in Loch Creran's main basin (except beneath fish farming cages) compared with

the upper basin, suggesting that naturally driven organic matter gradients also influence the foraminiferal assemblages of these sea lochs.

Only a few opportunistic species were able to tolerate the stressed environment associated with the high accumulation of organic matter input and without competition their populations were abundant (Pearson and Rosenberg, 1978). In this study, agglutinated species (e.g. *E. scabra*) were found in relatively high abundance in the upper basin and beneath fish farming sites (impacted areas); both can be considered indicative of a stressed environment. Several studies focusing on agglutinated benthic foraminiferal taxa conclude, based on similar results, that high abundances of these species are indicative of stressed environments (Alve & Murray, 1995; Alve, 2000; Murray et al., 2003). his suggests that agglutinated dominant assemblages may provide useful indicators and where similar assemblages of these species are found, conditions may be interpreted as impacted environments. Additionally, *E. selseyense* was common in such stressed environment, specifically at the upper basin samples and show a relatively good distribution in areas beneath farming sites; this species may also be able to tolerate lower salinity.

In the main basin, *A. beccarii* was common throughout the Loch Creran benthic foraminiferal assemblages sampled. The fairly high abundance of *A. beccarii* in sample assemblages was typically recorded and found in the reference samples and in samples collected at a distance from the farms. Hence, this suggest that this species is likely to prefer an unimpacted environment. Within the impacted assemblages, *A. beccarii* demonstrated a negative relationship with sediment organic matter content; typically, the diversity and abundance of this species declined at the impacted stations. The abundance reduction of this species indicates that sediment quality has changed, likely due to the effects of organic matter contents and hence, it could be utilised as an indicator to stressed environment since it cannot tolerate heavily loaded sedimentary organic matter conditions. Other species were also found in abundance in the main basin assemblages and demonstrated inverse relationships with sediment organic matter (OM) (e.g. *C. lobatulus* and *T. bockii*).

Although fish farming processes are likely to result in a change of sedimentary characteristics and hence influence the local benthic environment, further studies should be carried out on such environments to standardize the environmental impacts of such activities and focus on solutions to maintain the benthic habitat beneath these environments.

Attention should also be given to understanding the natural gradients of organic matter within fjord environments. Upper basin benthic foraminiferal assemblages are likely to be equally impacted by terrestrial organic matter (OM) input, thus sedimentary archives from these areas may provide useful comparative indicators of stressed environments with which to compare fish farming sites.

CHAPTER 5

TEMPORAL DISTRIBUTION OF BENTHIC FORAMINIFERA AND THEIR APPLICATION IN RECONSTRUCTING PALAEOENVIRONMENTS LINKED TO FISH FARMS IN LOCH CRERAN

CHAPTER 5

TEMPORAL DISTRIBUTION OF BENTHIC FORAMINIFERA AND THEIR APPLICATION IN RECONSTRUCTING PALAEOENVIRONMENTS LINKED TO FISH FARMS IN LOCH CRERAN

5.1 Introduction

Foraminiferal tests are valuable in preserving and recording the evidence of environmental stress through time, due to their high-test preservation potential and abundance in marine sediments (Yanko et at., 1999). Thus, they can be used as a key palaeoenvironmental proxy, providing historical baseline data for past environmental status (Murray, 1990; Shackleton, 1987). In order to understand and evaluate what effects various fish farm activities have had on the benthic environment, details are needed about the previous environmental conditions before fish production began; in some regions of the world, it is possible that such baseline data are absent. The main aim of this study is to quantify the potential to use benthic foraminiferal in the reconstruction of palaeoenvironmental changes linked to fish farming activity in Loch Creran. The impact of fish farming activity was analysed through total foraminiferal assemblage data, with a view to understanding the response of benthic foraminiferal faunas to temporal changes in fish farm inputs (e.g. organic material) which are considered to be

the main factor controlling the benthic foraminiferal assemblages in the underlying sediment (Jorissen et al., 1995; Chapter 4).

To establish the potential of benthic foraminifera for recording palaeoenvironments (i.e. the pre-impacted environment), two undisturbed sediment cores were carefully collected and examined to study the stratigraphic (temporal) distribution pattern of benthic foraminiferal components in Loch Creran on the west coast of Scotland. One core was chosen to represent the impacted station (beneath fish farming sites) SC-02-A, and the other core was collected at a distance from the farming cages (SC-04-B) (Figure 5.1). The sampling was performed using a Sholkovitz Corer (SC) to assess the stratigraphic variability of benthic foraminiferal assemblages in these environments. The depth profile of sediment organic matter (OM) contents was determined for each core and is presented in Chapter 3.

5.2 Sediment coring

The fish farm core (SC-02-A) was sampled every 1 cm down to 14 cm depth. The other core (SC-04-B) was collected as a representative of the non-fish farming samples (see chapter 4) and was sampled every 1 cm down to 11 cm. A total of 25 sub-samples from the two cores were processed and analysed

for grain size, organic matter (OM) content and for foraminiferal studies using the standard methods described earlier in chapter 2. The sampling location for the two sediment cores is illustrated in Figure 5.1. The aim is to determine faunal development at sites beneath fish farms and away from the farming cages and subsequently describe the overall palaeoenvironmental evolution at each core site. The samples were stored frozen until freeze-dried in the laboratory. For foraminiferal contents, the sediment samples were washed over nested sieve of 63-125 μm using a fine water spray. The sieved samples were left to oven dry at 40°C and then split into equal fractions using a micro-splitter. The total weight of the dry residues was then calculated. From each subsample, foraminiferal individuals were picked and a target of 300 specimens were collected using a fine artists paintbrush.

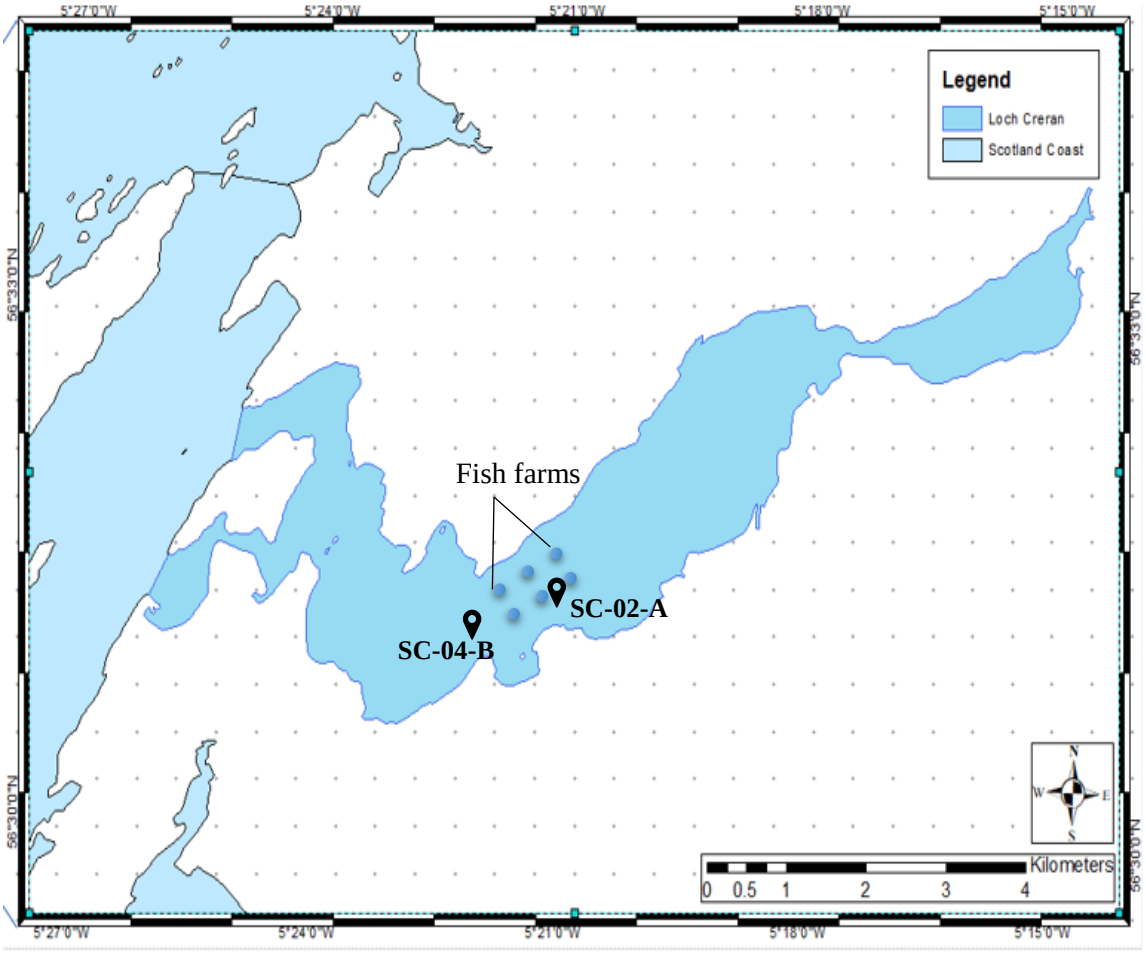


Figure 5. 1 Location map for the two selected core sites (SC-02-A and SC-04-B), Loch Creran.

5.3 Results

5.3.1 Vertical distribution of benthic foraminifera

5.3.1.1 Fish farming core site – SC-02-A

The study recognized a total of 18 foraminiferal species. The genera *Ammonia, Eggerella, Ammoscalaria* dominate the total foraminiferal composition followed by *Bulimina* and *Elphidium* (>5%) in the study core. The environmental parameters and the diversity index for this core are illustrated in Table 5.1. The common foraminiferal species identified in this core are listed in Table 5.2.

Obvious variations in the stratigraphic foraminiferal faunal composition were observed. Depending on the analytical results, the fish farm core site (SC-02-A) can be divided into an upper zone (from 1-6 cm) and a lower zone (from 7-14 cm) (Figure 5.2). The considerable changes in foraminiferal contents were associated with the shift to high organic matter (OM) contents in the uppermost sediments which were predominantly dark in colour (Figure 5.3). This transition in sediment type coincides with a clear decline in foraminiferal diversity during the early stage of changes, presumably coinciding with the onset and subsequent increase in fish farm production. Below 7 cm depth (lower zone), the dark organic-rich sediments give way to increasingly homogenous and lighter coloured miner-organic

sediments. Below 7 cm, both the foraminiferal abundances and diversity are higher. Moreover, individual foraminifera were often larger in size in the lower zone (pre-impacted environment). This suggests that sediments below this level (7 cm) are representative of the pre-impacted (before fish farms activity).

Ammonia beccarii was dominant in the lowermost depth and found in relatively large numbers from 7 cm to 14 cm. Whereas *Eggerella scabra* was particularly abundant between 1 cm to 5 cm (Figure 5.4). *Reophax* species were also present within the top 4 cm of the sediment stratigraphy. All other species have their maximum abundance in the lower core depth. When the sediments were checked, no shell debris was noticed except for a few broken fragments of molluscs. Carbonate content indicates a good correlation with species composition and abundance.

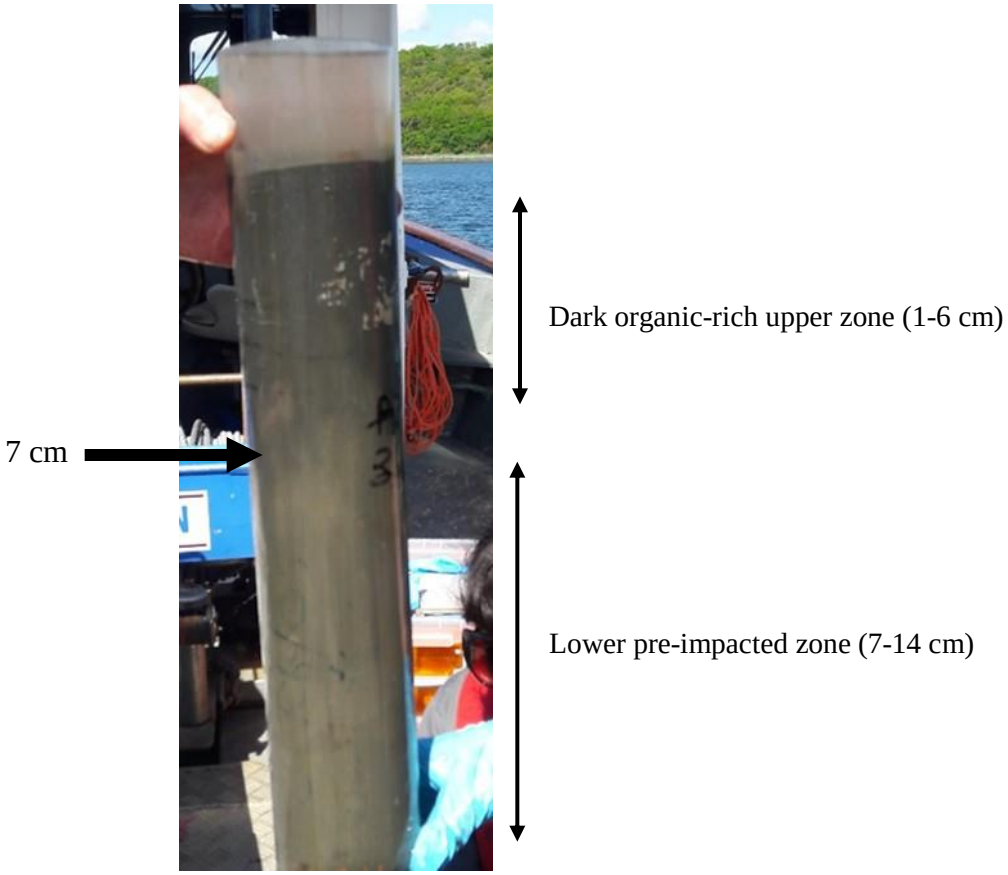


Figure 5. 2 illustrates the two zones in the fish farming core (SC-02-A). The arrow indicates the transition point from an upper dark organic-rich sediment (from 1-6 cm) to a lower pre-impacted zone (from 7-14 cm).

Table 5. 1 Results of environmental parameters, organic matter measurments and foraminiferal diversity indices of the fish farming core (SC-02-A).

Core id code	*Sediment intervals (cm)*	*Mean particle size*	*% Clay*	*% Silt*	*% Sand*	*%TC*	*%OC*	*%IC*	*%N*	*%TOM*	*%C*	*C/N ratio*	*Shannon_H*	*Fisher_alpha*
SC-02-A	0-1 cm	-	18.40	45	36.50	3.15	2.59	0.56	0.22	-	-	13.73	1.66	3.32
	1-2 cm	-	-	-	-	4.73	3.94	0.79	0.40	8.45	4.73	13.80	1.48	2.51
	2-3 cm	72.58	17.10	48.29	34.57	4.48	4.09	0.39	0.11	9.31	4.09	43.38	1.51	2.58
	3-4 cm	-	-	-	-	4.96	4.15	0.81	0.31	7.97	4.96	15.62	1.43	2.23
	4-5 cm	63.32	20.19	49.94	29.86	4.59	4.15	0.44	0.45	10.17	4.59	10.76	1.47	2.72
	5-6 cm	-	-	-	-	5.26	4.19	1.07	0.39	7.96	5.26	12.53	1.44	2.24
	6-7 cm	59.70	20.88	50.56	28.55	3.95	3.63	0.32	0.18	6.89	3.95	23.53	1.52	2.76
	7-8 cm	-	-	-	-	4.32	2.63	1.69	0.28	6.88	4.32	10.96	1.73	3.61
	8-9 cm	58.48	20.60	51.40	27.92	2.66	2.33	0.33	0.31	6.65	2.66	8.77	1.71	2.77
	9-10 cm	-	-	-	-	2.63	2.46	0.17	0.15	5.90	2.63	19.13	2.01	4.44
	10-11 cm	55.17	20.81	52.02	27.08	2.27	1.98	0.29	0.31	6.16	2.27	7.45	1.81	4.82
	11-12 cm	-	-	-	-	2.26	2.09	0.17	0.30	6.11	2.26	8.13	1.70	3.32
	12-13 cm	51.74	21.80	55.01	23.27	2.52	2.06	0.46	0.28	6.05	2.52	8.58	1.95	5.44
	13-14 cm	-	-	-	-	2.42	1.61	0.81	0.32	6.34	2.42	5.87	1.91	4.81
	14-15 cm	53.69	21.29	53.25	25.36	2.30	2.02	0.28	0.31	6.09	2.02	7.60	2.15	6.15

Table 5. 2 The vertical distribution and relative abundaces (%) of foraminifera for the fish farming core (SC-02-A).

Species	*0-1 cm*	*1-2 cm*	*2-3 cm*	*3-4 cm*	*4-5 cm*	*5-6 cm*	*6-7 cm*	*7-8 cm*	*8-9 cm*	*9-10 cm*	*10-11 cm*	*11-12 cm*	*12-13 cm*	*13-14 cm*
Reophax scotti	0.6	0.6	3	3	0	0	0	0	0	0	0	0	0	0
Reophax scorpiurus	0.3	0.9	0.9	1.3	0.3	0.3	0	0.6	1	1.2	0.6	0.3	0.6	1.3
Haplophragmoides bradyi	0.9	0.9	0.9	1.3	0	0.3	0.3	0.3	0.3	0	0	0	0.3	0.3
Ammoscalaria runiana	19.8	28.2	31.5	35.9	34.3	39	1	16	23	21	21	31	22	25.4
Textularia bocki	0	0	0	0	0	0	1	2.7	3.3	3	4.2	6	6.6	5.2
Eggerella scabra	38.5	38.2	39	36.3	35.9	30	31	25	19	18.9	22	16	18.7	15.4
Lagena striata	1.2	0	0	0	0	0	0	0	0	0.6	0.3	0	0	0.3
Stainforthia loeblochi	0.6	0	0	0	0	0	0	0.3	0	0.3	0.3	0	0.6	0
Oolina williamsoni	0	0	0	0	0.3	0.6	0	0	0	0	0.3	0	0.6	0.6
Bolivina pseudoplicata	0	0	0	0	0	0	0	0.3	0	0.3	0.3	0.3	0.6	0.3
Bulimina elongata	0.3	0.3	0.3	0.6	0.9	1	1.3	1	1.6	1.5	1	2.6	0.3	0
Bulimina marginata	7.6	2.7	4.5	2.3	3.1	4.6	4.6	5.6	7	6.9	3	2	3.6	4.9
Asterigerinata mamilla	1.8	1.3	0.6	0	0	1	1.3	2.3	1.3	1.2	0.6	0.6	1.9	0.6
Ammonia beccarii	25.3	21.9	17.2	18.4	19.6	20	30	34	37	29.6	36	35	35	34.4
Elphidium aculeatum	0	0	0	0	0.3	0	0	0.3	0.6	0.3	1	0.3	0	0.9
Elphidium selseyense	2.1	1.3	3	2.6	2.5	1.3	1	5.3	2.6	3.4	1.3	3.6	4.6	4.2
Cibicides lobatulus	0	0	0	0	0	0	0	1	1	1.8	2.6	3.6	2.6	2.9
Nonionella turgida	0	0	0	0	0	0	0	0	0	1.2	0.6	0.3	0.3	0.3

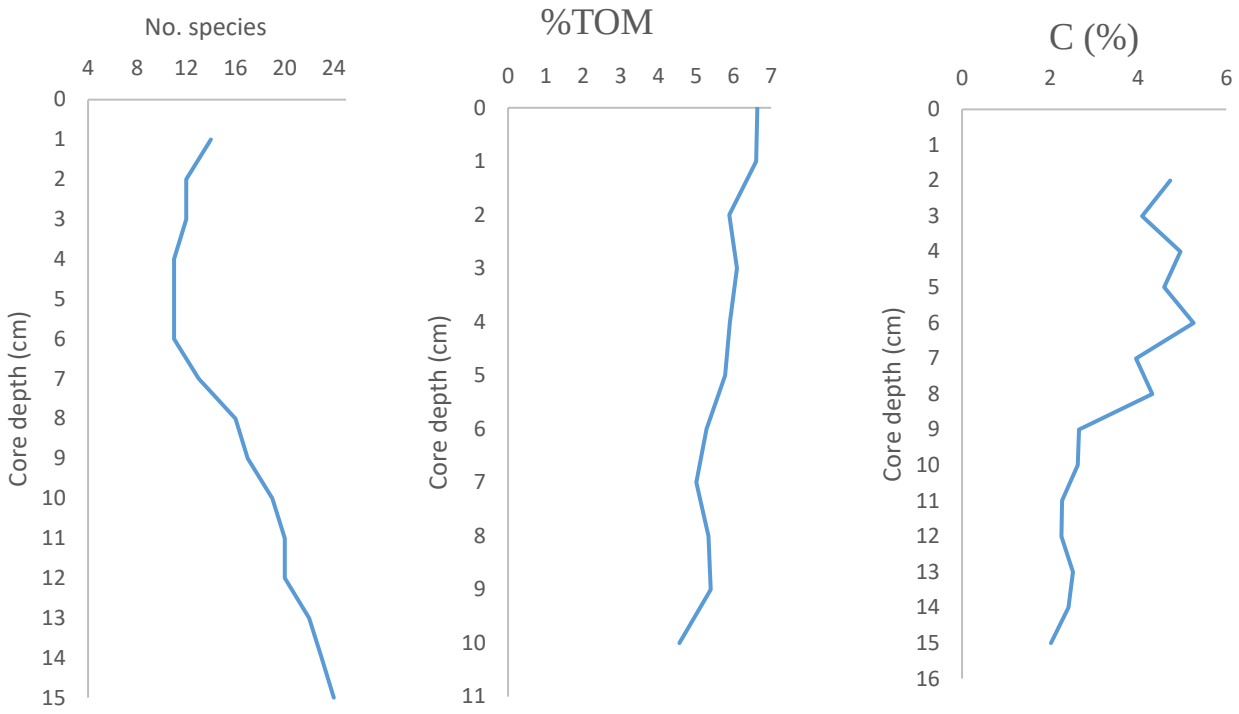


Figure 5. 3 Vertical profile of number of foraminiferal species in each depth interval in relation to the %TOM and %C at the fish farming core site (SC-02-A). The plot illustrates the changes in foraminiferal richness in association to high %OM and %C contents in the uppermost sediments.

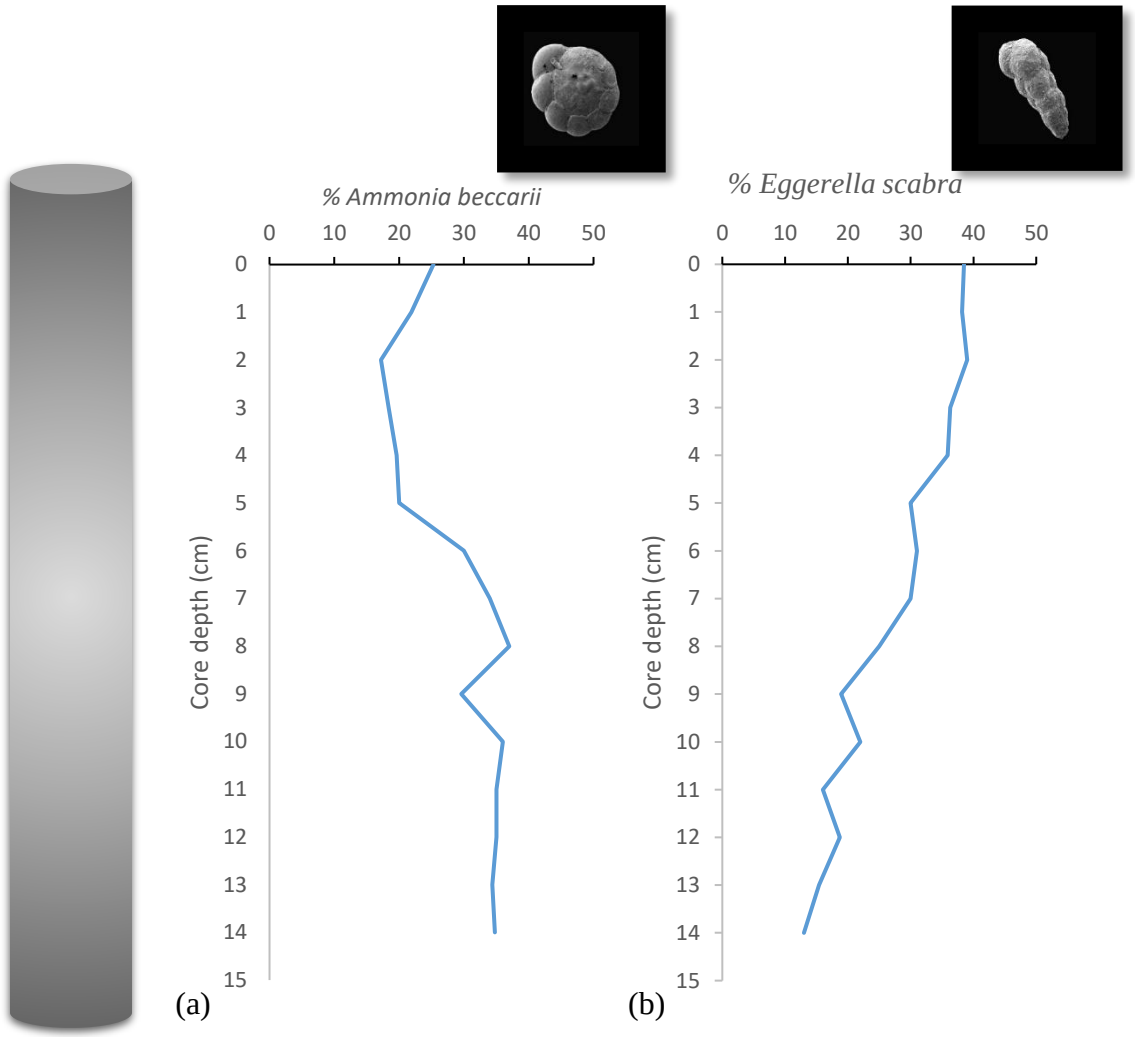


Figure 5. 4 Two species were dominant in the fish farming core site (SC-02-A). (a) *Ammonia beccarii* was dominant, and almost stable, in the lowermost depth and found in relatively large numbers from 7 cm to 14 cm. Whereas (b) *Eggerella scabra* was particularly abundant between 1 cm to 5 cm depth.

5.3.1.2 Non-fish farming core site – SC-04-B.

The analytical results for the non-fish farming core site (SC-04-B) identified a total of 21 foraminiferal species. Overall, the vertical distribution pattern of benthic foraminifera at this core site was observed to be almost stable throughout the core, with no significant assemblage changes observed. The overall foraminiferal abundances were, however, generally noted to be more diverse in the deeper sediments, with slight changes noted up-core to the surface. Table 5.3 list the environmental parameters and the diversity indices for this core. The common foraminiferal taxa found for core SC-04-B with their relative abundances are listed in Table 5.4.

The total %OM and the %C content in the analysed samples were noted to be relatively stable throughout the core ranging from 4.56 to 6.63% and 1.38 to 3.27%, respectively (Figure 5.5). The most dominant genera were *Ammonia, Ammoscalaria* and *Eggerella,* with an average relative abundance of 34.4%, 20.9% and 17.2%, respectively. Other species were also found abundances (>2%) throughout the core, including, *B.marginata, E.selseyense*, *T.bockii*, and *C.lobatulus,* with average abundances of 6.7%, 3.9%, 3.7% and 2%, respectively.

Table 5. 3 Results of environmental parameters, organic matter measurments and foraminiferal diversity indices for the non-fish farming core site (SC-04-B).

Core id code	*Sediment intervals (cm)*	*Mean particle size*	*% Clay*	*% Silt*	*% Sand*	*%TOM*	*%N*	*%C*	*C/N ration*	*Shannon_H*	*Fisher_alpha*
SC-04-B	0-1 cm	79.6	14.3	42.6	42.8	6.63	0.19	3.27	20.08	1.74	6.01
	1-2 cm	85.3	11.1	43.0	45.8	-	0.94	2.32	2.88	1.97	7.50
	2-3 cm	60.1	14.9	49	36.0	5.88	0.19	2.12	13.02	1.87	5.37
	3-4 cm	-	-	-	-	6.09	0.21	2.85	15.83	1.88	6.44
	4-5 cm	59.7	16.9	49.4	33.5	5.90	0.22	2.61	13.84	1.82	4.38
	5-6 cm	-	-	-	-	5.78	0.16	2.53	18.45	1.72	5.71
	6-7 cm	59.6	15.6	51.9	32.2	5.28	0.15	2.43	18.9	1.90	6.46
	7-8 cm	-	-	-	-	5.01	0.19	2.24	13.75	2.02	7.40
	8-9 cm	56.7	19.0	51.0	29.9	5.33	0.15	1.94	15.09	2.06	7.01
	9- 10 cm	-	-	-	-	5.39	0.13	1.95	17.5	2.03	6.47
	10-11 cm	58.6	16.9	53.2	29.8	4.56	0.09	1.38	17.89	1.78	5.04

5. 4 The vertical average relative abundances of foraminiferal for the non-fish farming core site (SC-4-B).

Species	*0-1 cm*	*1-2 cm*	*2-3 cm*	*3-4 cm*	*4-5 cm*	*5-6 cm*	*6-7 cm*	*7-8 cm*	*8-9 cm*	*9-10 cm*	*10-11 cm*
Reophax scorpiurus	1.1	0.4	0.8	1.3	1.3	1.5	0.8	1.3	2.9	1.5	1.2
Haplophragmoides bradyi	0	0.8	0.4	0.4	0.4	0	0.4	0.4	0	0.3	0
Ammoscalaria runiana	20.2	17.2	22	21.7	23.1	17.4	21.4	23.6	21.4	19.3	22.8
Textularia bocki	1.4	0.8	2.5	2.6	3.1	2.2	4.7	9	7.1	3.8	3.6
Eggerella scabra	28.9	25.2	20.7	14.2	15.5	16	16.7	11.3	12.1	14.6	15
Lagena striata	0	0.4	0	0	0	0.3	0.4	0	0	0	0
Stainforthia loeblichi	0	0	0.4	0	0	0	0.4	0.4	0.8	0.3	0
Oolina williamsoni	1.1	0.4	0.8	1.3	0.8	0.3	0.8	1.3	1.2	1.1	0.8
Fisssurina elliptica	0.5	0.4	0	0	0	0.3	1.2	0.9	0.8	1.5	0.4
Fissurina lucida	0.2	0.8	0.4	0.4	0.4	0	0	0.4	0	0	0
Bolivina pseudoplicata	0.2	0	0	0	0.4	0.6	0	0	0.4	1.5	0.4
Bolivina skagerrakeniss	0	0	0	0	0	0.3	1.7	0.4	0.4	0.7	0.8
Bulimina elongata	0.8	2.3	1.6	1.3	2.6	0	0.4	0.4	1.6	1.1	0.4
Bulimina marginata	12	12.1	8.8	7.1	7.1	4.7	5.5	5	4.6	4.6	2.4
Asterigerinata mamilla	0.5	2.3	0	3.5	2.2	1.9	1.2	2.2	2.9	1.5	1.2
Ammonia beccarii	25.4	27.4	31.7	38.6	39.1	38	36.4	36.3	34.4	35.9	35.5
Elphidium aculeatum	0.2	0.4	0.4	1.3	0	0.9	0	1.8	0	1.5	0.4
Elphidium margaratecium	0.2	0.4	0	0	0	0	0.8	0.4	1.2	0	0
Elphidium selseyense	1.7	7	6.3	2.2	3.1	1.9	3	4.5	2.9	3.8	6.9
Cibicides lobatulus	1.1	0.8	2.1	1.3	3.1	1.5	2.1	2.2	2.1	4.2	2
Nonionella turgida	0.2	0.4	0.8	0.4	0	0	0	0.4	0	0	0

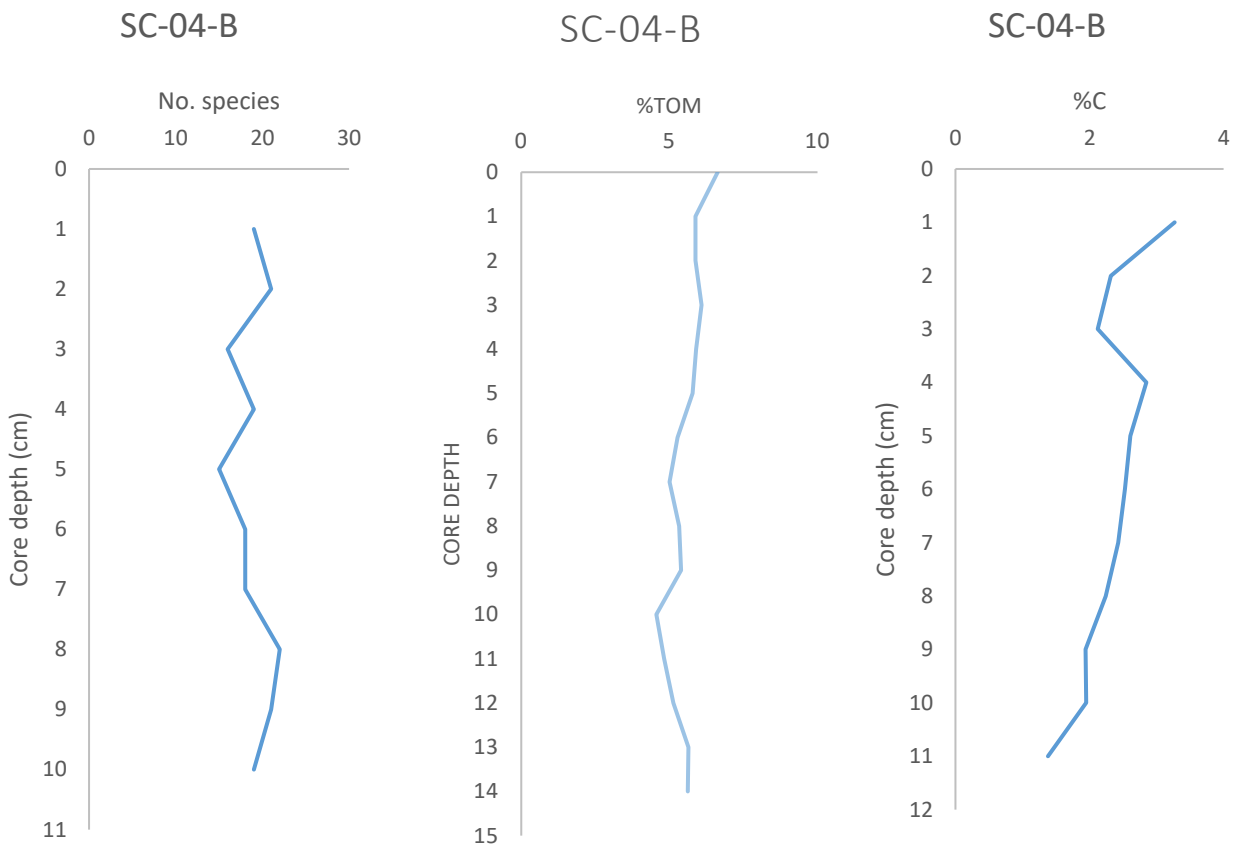


Figure 5. 5 Vertical profile of number of foraminiferal species in each depth interval in relation to the %TOM and %C at the non-fish farming core site (SC-04-B). The plot showing the generally stable richness measures of the foraminiferal species throughout the core in association to %OM and %C contents in throughout the core sediments.

5.4 Discussion

By studying the vertical distribution patterns of benthic foraminifera (and studying their abundance, diversity and species richness) we can begin to understand the environmental (baseline) conditions before the onset of fish farming. Therefore, one needs to have a thorough understanding of the modern foraminiferal surface assemblages before making interpretations based on vertical distributions and abundances of benthic foraminifera.

The grain size analysis in the fish farming core (SC-02-A) showed a uniform grain size distribution with no obvious signs of varying sediment size down-core (see chapter 3). However, the total organic matter (OM) contents in the fish farming core sediments were low below 7 cm depth but higher towards the top of the core (i.e. above 6 cm depth). This change can be explained and linked to the considerable quantity of organic matter received from fish farming activities. In the sediments deposited between 1 – 6 cm, foraminifera were abnormally small in size, suggesting a stressed environment for healthy growth and a potentially different reproductive strategy. Moreover, since, there is lack of oxygenated conditions (low DO_2 concentration), the benthic foraminifera must have consumed whatever little DO_2 available in the substratum for survival and this may have reduced their growth rate. Overall, the depth relative abundance of foraminifera at the fish

farm site showed a gradual decline upwards in the core towards the surface sediment, whereas the highest species relative abundance was observed towards the bottom part of the core. Conversely, for the core from the non-fish farming site, the foraminiferal relative abundance was comparatively high throughout the core. Species diversity was generally high, and the foraminifera were relatively large, while the OM content was typically stable and relatively low throughout the core.

Two species: *Ammonia beccarii* and *Eggerella scabra*, were dominant in the vertical profile for the fish farming core. The first species was found in relatively large numbers in the lower core zone (i.e. from 7 cm to 14 cm), whereas the second species was particularly abundant in the upper zone (i.e. from 1 cm to 5 cm). *Reophax* species were also present within the top 4 cm of the sediment stratigraphy. All other species have their maximum abundance in the lower core depth. The carbonate content is also lower through the middle section of this core. When the sediments were checked, no shell debris was noticed except for a few broken fragments of molluscs. Carbonate content indicates a good correlation with species composition and relative abundance.

5.5 Conclusion

The vertical distribution of the foraminifera is particularly dependent on the flux of OM to the seafloor. Due to fish farm environmental conditions and the high accumulation of the OM contents, two species *A.beccarii* and *E.scabra* are abundant and can withstand in these locally impacted benthic environments (Phleger and Soutar 1973; Hornung et al., 1989; Alve, 1991; Alve and Bernhard 1995; Bernhard et al. 1997; Bernhard and Bowser 1999). The foraminiferal average relative abundance is higher towards the bottom of the core at the fish-farming site. The low species diversity and small size of tests can be ascribed to high OM contents. Beneath the fish cages, there is a detectable visual effect on sediment colour caused by loading of organic matter, fish food and faecal material, and there is an obvious environmental down-core OM contamination suggested from the foraminifera distribution. Fish farming have a clear environmental impact detected in the foraminiferal data and visible evidence in the sediment to suggest high organic matter (OM) loading. Foraminiferal data in cores provide the promising evidence of obtaining information on benthic habitats in these environments. The downward organic flux, which controls the complex relation between food and oxygen availability in the benthic environment, appears to be the main factor determining the distribution of benthic foraminifera.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH PERSPECTIVE

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH PERSPECTIVE

This chapter seeks to address the research objectives outlined in chapter 1 and identify future challenges and perspectives in this field of study. The main objective of this study was to evaluate the applicability of benthic foraminifera as a novel bio-monitoring tool to assess the environmental impacts linked to organic matter (OM) enrichment of marine sediments from a variety of sources. Many studies have shown that foraminifera are important biological components within marine communities and can be useful indicators of the overall health of a marine environment (Alve, 1995; Pati and Patra, 2011). Mapping and understanding the response of benthic foraminiferal communities to environmental changes will help to develop new approaches to assess and monitor the quality status of the marine environment. In this study, natural and anthropogenic induced environmental changes, especially those linked to OM enrichments, on benthic foraminifera communities in Loch Creran, on the west coast of Scotland were investigated to accomplish the objectives of this study.

6.1 **Research objective 1: To investigate the main environmental parameters controlling benthic foraminiferal distribution in Loch Creran (Chapter 3).**

River Creran at the head of Loch Creran and the expected increase in fish farming activities within the main basin of Loch Creran play an important role in delivering organic matter into the benthic marine environment here and similarly elsewhere on the west coast of Scotland. In order to investigate and evaluate changes in the structure of benthic foraminiferal communities, environmental parameters were identified in the studied area in an attempt to assess the environmental impact on foraminiferal distribution. In this study, the dissolved oxygen (DO_2) in bottom water, the amount of organic matter (OM) content in the sediment and sediment grain size were measured as representative environmental parameters to indicate the ecological conditions of the benthic environment. Many studies have concluded that DO_2 is considered to be one of the environmental parameters controlling the foraminiferal distribution (e.g. Gooday 1986; Corliss and Chen 1988; Mackensen and Douglas 1989; Corliss and Emerson 1990; Barmawidjaja et al. 1992; Jorissen et al. 1992; Rosoff and Corliss 1992; Rathburn and Corliss 1994; Jorissen et al. 1995). Furthermore, in this study, the OM beneath and surrounding the fish cages, and in fjord sediments in the upper basin of Loch Creran (river influenced) was investigated. The results show that two

environmental parameters (i.e. DO_2 and OM contents) generally control and affect the distribution of benthic foraminifera (Murray, 1973; Alejoet al. et., 1999).

The environment in the upper basin (river influence) and the farming sites in Loch Creran are highly enriched with organic matter inputs due to the long-term accumulation of terrestrial organic matter (soils, leaf litter etc.). at the mouth of River Creran and due to daily fish farms activities. Similar studies have documented elevated levels of OM in the sediments directly below fish farms and decreasing concentrations with distance from the point source (e.g., Lee et al. 2006; Loubere p., 1999). Furthermore, studies have shown that various sources of organic matter enrichment are the most common forms of disturbance in the benthos (Weston, 1990; Gee et al., 1985).

Detailed benthic foraminiferal assemblage investigations were performed in this study in combination with characterizations of the environmental parameters, i.e. sediment properties, temperature, water depth and dissolved oxygen concentration in both contaminated and un-impacted areas (stations away from farming sites). To strengthen the importance and acceptance of benthic foraminifera as indicators and as a bio-monitoring tool,

it is also crucial that the standardized methodology developed by (FOBIMO) (Schönfeld. et al., 2012) is adopted to enable comparison of environments.

6.2 **Research objective 2: Understanding how benthic foraminiferal distribution respond to the environmental impacts linked to organic matter enrichment (Chapter 4).**

Recently, benthic foraminifera have been extended to investigations of natural and anthropogenic impacts on the marine environment. Many studies have shown that benthic foraminifera are one of the most sensitive and competitive faunal proxy indicators available for indicating any changes in marine environments (Culver and Buzas, 1995; Buzas et al. 2003). In this study we aimed to understand some of the ways that benthic foraminiferal distribution patterns reflect the environmental changes linked to fish farming and provide assessment of the record on recent and past environments. Many studies have concluded that the distribution of foraminifera can provide significant indication of high organic-rich contamination in impacted and non-impacted environments (Haynes, 1960, 1970; Cummins, 1979). Moreover, diversity and the relative abundance have been considered as the most reliable environmental indictors because, in general, they tend to decrease in impacted environments where heavy pollutant concentrations occur (Cearreta et al., 2002; Debenay et al., 2001; Armynot du Chàtelet et al., 2004).

A baseline data set of the spatial distribution pattern of benthic foraminifera was established in Loch Creran on the west coast of Scotland. A general distribution pattern of benthic foraminifera was documented and the relationship between foraminiferal communities and environmental variables was elucidated. Overall, benthic foraminiferal population diversity and density were lowest to the impacted close to fish farming cages. The analytical study of the spatial distribution of benthic foraminifera has resulted in identification of four broad ecological assemblage groups - the grouping is mainly dependent on the different responses of these species to DO_2 concentration and OM enrichment which resulted in decreasing foraminiferal diversity. Many scientists have reported the same results and concluded that these two variables (i.e. oxygen deficient and OM enrichment) have direct environmental impacts on the distribution of benthic foraminifera (Phleger and Soutar 1973; Hornung et al., 1989; Alve, 1991; Alve and Bernhard 1995; Bernhard et al. 1997; Bernhard and Bowser 1999).

Certain agglutinated species (e.g. *E. scabra* in this study) are capable of surviving anoxia and have been found in high relative abundance in impacted areas, both here and elsewhere (Bernhard and Alve 1996). These results from Loch Creran have species in common with foraminiferal assemblages described from nearby Loch Etive by Murray (2003); who also

noted certain similarities to the assemblages of some southern Norwegian fjords (Alve and Nagy, 1986; Alve, 1995). This suggests that assemblages dominated by agglutinated taxa may provide useful indicators for impacted environment. Several studies have reached similar conclusions, where high abundances of agglutinated species characterize stressed environments (Alve & Murray, 1995; Alve, 2000; Murray et al., 2003).

6.3 **Research objective 3: To establish the potential of benthic foraminifera for recording the long-term environmental impact of fish farming (Chapter 5).**

The main aim of this study is to quantify the potential to use benthic foraminiferal in the reconstruction of palaeoenvironmental changes linked to fish farming activity in Loch Creran. Studies have shown that foraminifera are used as a key palaeoenvironmental proxy providing historical baseline data for past environmental status (Murray, 1990; Shackleton, 1987). Generally, foraminifera often show temporal (down-core) zonation that can be used to document pre-impacted environments (palaeoenvironment) (Bernhard, 1993; Moodely et al., 1997). Thus, the stratigraphic distribution of benthic foraminifera can be utilised for future environmental monitoring where prior knowledge of the previous environment before disturbance may be absent (e.g., Clark, 1971; Grant et al., 1995; Scott et al., 1995; Hallock et al., 2003).

In this study, there were significant variations in the stratigraphic foraminiferal faunal composition beneath fish farming sites. Considerable changes in foraminiferal diversity (a clear decline) were associated with the shift to high organic matter (OM) contents in the uppermost sediments of the fish farming core site. The early stage of change, presumably coinciding with the onset and subsequent increase in fish farm production, are clear in both the sediment and faunal stratigraphy. Below this impacted point (before fish farm production) the foraminiferal abundance and diversities were high. At the sites away from the farming cages, the overall vertical distribution pattern of benthic foraminifera was noted to be almost stable throughout the core, with no significant assemblage changes observed. In general, the low species diversity and small test size in the fish farm core were linked to high sediment organic matter content, whereas foraminiferal abundance and diversity were comparatively high throughout the non-fish farming site and foraminifera at these sites were also relatively large.

These findings may conclude:

1- Since foraminifera have a short life history, that they respond quickly to environmental changes whether they are natural or anthropogenic.

2- Many opportunistic species benefit from high organic matter content, either directly or indirectly through increased nutrition (organic substance) or indirectly, through reduced competition and predation.

The following main conclusions were reached based upon the results presented in this thesis:

- In the impacted stations in Loch Creran, stress tolerant species dominate the assemblages, reflecting the different anthropogenic stressors active and linked to aquaculture. In Loch Creran, both living and dead assemblages reflect the natural variability of the physical environment of the region.

- Stressors, having direct or indirect influence on the foraminiferal assemblages of Loch Creran, are: (a) disturbance of the sediments by accumulation of organic matter; (b) persistent organic matter content

and; (c) the inflow of fresh river water, which lowers the salinity of fjord.

- The living foraminiferal assemblages in Loch Creran can be characterized by: (a) species tolerating higher sediment organic matter content; (b) species associated with un-impacted environments and sufficient food availability, but lower sediment OM content, and; (c) species with no clear habitat preference or spatial distribution pattern.

- The foraminiferal community composition is very promising indicator of organic matter enrichment linked to marine aquaculture. Where naturally high OM contents are observed (e.g. River Creran), the foraminiferal communities are distinct, and this will aid in the distinct of anthropogenic from natural sources of organic matter impacts from past environments.

6.4 **Future work**

The upper basin benthic foraminiferal assemblages are likely to be extremely impacted by terrestrial organic matter (OM) input, thus sedimentary archives from this natural organic-rich environment may provide useful palaeorecords of environmental change in the future, particularly if the input of terrestrial OM into the sea loch has changed over time.

Progress towards a benthic foraminifera bio-monitoring tool on the west coast of Scotland has been achieved, but there are numerous questions concerning benthic foraminiferal responses to marine and river pollution that require further investigation. However, thus study has shown clearly, that the past, present and future impacts of marine aquaculture on the benthic marine environment can be detected with confidence using foraminifera as a novel bio-monitoring tool.

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APPENDICES

APPENDIX 1 – FORAMINIFERAL DATA

Table: 4.1 Taxonomical classification of foraminiferal species in Loch Creran

- TEXTULARIA
  - *Reophax scotti Chaster*
  - *Reophax scorpiurus Montfort*
  - *Reophax fusiformis (Williamson)*
  - *Haplophragmoides brayi (Robertson)*
  - *Ammoscalaria runiana (Heron-Allen and Earland)*
  - *Textularia bocki Höglund*
  - *Eggerella scabra (Williamson)*
  - *Trochammina sp*
- MILIOLINA
  - *Quinqueloculina seminulum (Linnė)*
  - *Quinqueloculina sp.*
- ROTALIINA
  - *Amphicorina scalaris*
  - *Lagena perlucida (Montagu)*
  - *Lagena calvata (d'Orbigny)*
  - *Lagena striata (d'Orbigny)*
  - *Stanforthia loeblichi (Feyling-Hanssen)*
  - *Stanforthia fusiformis (Williamson)*
  - *Oolina hexagona (Williamson)*
  - *Oolina squamosa (Montagu)*
  - *Oolina melo d'Orbigny*
  - *Oolina williamsoni (Alcock)*

- *Fissurina elliptica (Cushman)*
- *Fissurina lucida (Williamson)*
- *Bolivina pseudoplicata Heron-Allen*
- *Bolivina peseudoplunctata Höglund*
- *Bolivina skagerrakeniss Qvale and Nigam*
- *Bolivina spathulata (Williamson)*
- *Bulimina elongate d'Orbigny*
- *Bulimina marginata d'Orbigny*
- *Buccella frigida (Cushman)*
- *Rosalina sp. d'Orbigny*
- *Asterigerinata mamilla (Williamson, 1858)*
- *Ammonia beccarii (Linne)*
- *Elphidium aculeatum (d'Orbigny)*
- *Elphidium albiumbilicatum (Wiess 1954)*
- *Elphidium margaritaceum (Cushman)*
- *Elphidium gerthi Voorthuysen*
- *Elphidium williamsoni Haynes*
- *Elphidium selseyense (Heron-Allen & Earland)*
- *Cibicides lobatulus (Walker and Jacob)*
- *Nonionella turgida (Wlliamson)*
- *Uvigerina peregrine Cushman*

FORAMINIFERAL SPECIES COUNTS- SURFACE SAMPLES

Species / stations	CC-01-A	CC-01-B	CC-01-C	SC-02-A	CC-02-B	CC-02-B	CC-03-A	CC-03-B	CC-03-C	SC-04-A	SC-04-B	SC-05-A	SC-06-A	SC-07-A	SC-08-A	GB-03-C	GB-07-A	GB-09-A	GB=20-A	GB-28-A
Reophax scotti	0.00	0.00	0.00	5.00	8.00	4.00	3.00	3.00	6.00	0.00	1.00	0.00	1.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00
Reophax scorpiurus	7.00	4.00	5.00	1.00	2.00	2.00	4.00	3.00	3.00	4.00	1.00	4.00	2.00	7.00	8.00	0.00	0.00	0.00	4.00	4.00
Haplophragmoides b bradyi	4.00	2.00	3.00	3.00	1.00	2.00	1.00	1.00	2.00	0.00	2.00	1.00	3.00	6.00	5.00	0.00	0.00	1.00	3.00	1.00
Ammoscalaria runiana	30.00	19.00	20.00	50.00	66.00	50.00	62.00	65.00	63.00	65.00	60.00	54.00	58.00	55.00	45.00	7.00	8.00	10.00	65.00	60.00
Textularia bocki	12.00	13.00	17.00	0.00	0.00	1.00	6.00	5.00	3.00	5.00	3.00	4.00	0.00	4.00	10.00	0.00	0.00	0.00	8.00	11.00
Trochammina sp.	1.00	2.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	1.00	0.00	0.00	0.00	2.00	0.00	0.00	0.00	0.00	0.00
Eggerella scabra	45.00	54.00	53.00	123.00	124.00	130.00	112.00	103.00	123.00	80.00	75.00	64.00	129.00	75.00	54.00	193.00	190.00	185.00	65.00	62.00
Quinqueloculina seminulum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Quinqueloculina sp.	1.00	1.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00	2.00	0.00	1.00
Amphicorina scalaris	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lagena perlucida	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lagena calvata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00	0.00	0.00	0.00	0.00	0.00
Lagena striata	1.00	0.00	0.00	4.00	0.00	0.00	3.00	0.00	0.00	0.00	1.00	3.00	0.00	1.00	2.00	4.00	0.00	0.00	1.00	1.00
Stanforthia loeblichi	2.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	2.00	0.00	0.00	1.00	1.00
Stanforthia fusiformis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.00	0.00	0.00	0.00	0.00	0.00

Oolina hexagona	4.00	3.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Oolina squamosa	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Oolina melo	2.00	3.00	2.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00
Oolina williamsoni	5.00	4.00	6.00	0.00	0.00	0.00	1.00	0.00	0.00	4.00	4.00	4.00	0.00	1.00	1.00	0.00	0.00	0.00	2.00	3.00
Fisssurina elliptica	5.00	4.00	4.00	2.00	0.00	0.00	0.00	0.00	0.00	2.00	1.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Fissurina lucida	5.00	2.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	2.00	0.00	0.00	2.00	0.00	0.00	0.00	1.00	1.00
Bolivina pseudoplicata	3.00	7.00	3.00	0.00	0.00	0.00	0.00	1.00	2.00	0.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00
Bolivina pseudopunctata	2.00	3.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00	0.00	0.00	0.00	1.00	1.00
Bolivina skagerrakeniss	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Bolivina spathulata	3.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	1.00
Bulimina elongata	9.00	8.00	10.00	4.00	3.00	4.00	5.00	4.00	2.00	3.00	5.00	8.00	0.00	1.00	4.00	8.00	10.00	9.00	6.00	4.00
Bulimina marginata	7.00	5.00	8.00	15.00	12.00	15.00	11.00	15.00	8.00	16.00	15.00	21.00	14.00	23.00	20.00	4.00	5.00	6.00	17.00	16.00
Buccella frigida	3.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rosalina sp.	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Asterigerinata mamilla	17.00	20.00	18.00	4.00	1.00	3.00	5.00	4.00	5.00	3.00	5.00	5.00	1.00	5.00	7.00	0.00	0.00	0.00	1.00	4.00
Ammonia beccarii	76.00	87.00	96.00	77.00	71.00	70.00	72.00	75.00	67.00	94.00	100.00	102.00	75.00	90.00	86.00	10.00	8.00	16.00	85.00	87.00
Elphidium aculeatum	9.00	11.00	10.00	0.00	0.00	2.00	2.00	0.00	0.00	2.00	1.00	0.00	0.00	0.00	3.00	0.00	0.00	0.00	2.00	3.00

Elphidium margaritaceum	5.00	3.00	5.00	1.00	0.00	0.00	3.00	2.00	2.00	1.00	2.00	0.00	0.00	2.00	1.00	0.00	0.00	0.00	0.00
Elphidium gerthi	5.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Elphidium albiumbilicatum	0.00	4.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00
Elphidium williamsoni	2.00	4.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00	1.00
Elphidium selseyense	7.00	8.00	7.00	9.00	10.00	16.00	10.00	14.00	11.00	12.00	16.00	14.00	15.00	22.00	18.00	72.00	77.00	69.00	24.00	20.00
Cibicides lobatulus	12.00	15.00	13.00	0.00	1.00	1.00	0.00	2.00	2.00	5.00	2.00	4.00	0.00	0.00	9.00	0.00	0.00	1.00	8.00	14.00
Nonionella turgida	7.00	6.00	9.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	1.00	4.00	0.00	0.00	1.00	5.00	1.00
Adercotytryma glomeratume	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.00	0.00	0.00	0.00	0.00	0.00
Haynesina germanica	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Uvigirina perigrina	0.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00

FORAMINIFERAL RELATIVE ABUNDANCES- SURFACE SAMPLES

Species / stations	% CC-01-A	%CC-01-B	%CC-01-C	%CC-02-A	%CC-02-B	%CC-02-C	%CC-03-A	%CC-03-B	%CC-03-C	%SC-04-A	%SC-04-B	%SC-05-A	%SC-06A	%SC-07-A	%SC-08-A	%GB-03-C	%GB-07-A	%GB-09-A	%GB-20-A	%GB-28-A
Reophax scotti	0.0	0.0	0.0	1.7	2.7	1.3	1.0	1.0	2.0	0.0	0.3	0.0	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0
Reophax scorpiurus	2.3	1.3	1.7	0.3	0.7	0.7	1.3	1.0	1.0	1.3	0.3	1.3	0.7	2.3	2.7	0.0	0.0	0.0	1.3	1.3
Haplophragmoidesb bradyi	1.3	0.7	1.0	1.0	0.3	0.7	0.3	0.3	0.7	0.0	0.7	0.3	1.0	2.0	1.7	0.0	0.0	0.3	1.0	0.3
Ammoscalaria runiana	10.0	6.3	6.7	16.7	22.0	16.7	20.7	21.7	21.0	21.7	20.0	18.0	19.3	18.3	15.0	2.3	2.7	3.3	21.7	20.0
Textularia bocki	4.0	4.3	5.7	0.0	0.0	0.3	2.0	1.7	1.0	1.7	1.0	1.3	0.0	1.3	3.3	0.0	0.0	0.0	2.7	3.7
Trochammina sp.	0.3	0.7	0.0	0.3	0.3	0.0	0.0	0.3	0.3	0.0	0.3	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0
Eggerella scabra	15.0	18.0	17.7	41.0	41.3	43.3	37.3	34.3	41.0	26.7	25.0	21.3	43.0	25.0	18.0	64.3	63.3	61.7	21.7	20.7
Quinqueloculina seminulum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Quinqueloculina sp.	0.3	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.0	0.3
Amphicorina scalaris	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lagena perlucida	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lagena calvata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0
Lagena striata	0.3	0.0	0.0	1.3	0.0	0.0	1.0	0.0	0.0	0.0	0.3	1.0	0.0	0.3	0.7	1.3	0.0	0.0	0.3	0.3
Stanforthia loeblichi	0.7	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.3	0.3
Stanforthia fusiformis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0
Oolina hexagona	1.3	1.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
Oolina squamosa	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
Oolina melo	0.7	1.0	0.7	0.3	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.0
Oolina williamsoni	1.7	1.3	2.0	0.0	0.0	0.0	0.3	0.0	0.0	1.3	1.3	1.3	0.0	0.3	0.3	0.0	0.0	0.0	0.7	1.0

Fisssurina elliptica	1.7	1.3	1.3	0.7	0.0	0.0	0.0	0.0	0.0	0.7	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
Fissurina lucida	1.7	0.7	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.7	0.0	0.0	0.7	0.0	0.0	0.0	0.3	0.3
Bolivina pseudoplicata	1.0	2.3	1.0	0.0	0.0	0.0	0.0	0.3	0.7	0.0	0.3	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.3	0.3
Bolivina pseudopunctata	0.7	1.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.3	0.3
Bolivina skagerrakeniss	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Bolivina spathulata	1.0	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.3
Bulimina elongata	3.0	2.7	3.3	1.3	1.0	1.3	1.7	1.3	0.7	1.0	1.7	2.7	0.0	0.3	1.3	2.7	3.3	3.0	2.0	1.3
Bulimina marginata	2.3	1.7	2.7	5.0	4.0	5.0	3.7	5.0	2.7	5.3	5.0	7.0	4.7	7.7	6.7	1.3	1.7	2.0	5.7	5.3
Buccella frigida	1.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rosalina sp.	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Asterigerinata mamilla	5.7	6.7	6.0	1.3	0.3	1.0	1.7	1.3	1.7	1.0	1.7	1.7	0.3	1.7	2.3	0.0	0.0	0.0	0.3	1.3
Ammonia beccarii	25.3	29.0	32.0	25.7	23.7	23.3	24.0	25.0	22.3	31.3	33.3	34.0	25.0	30.0	28.7	3.3	2.7	5.3	28.3	29.0
Elphidium aculeatum	3.0	3.7	3.3	0.0	0.0	0.7	0.7	0.0	0.0	0.7	0.3	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.7	1.0
Elphidium margaritaceum	1.7	1.0	1.7	0.3	0.0	0.0	1.0	0.7	0.7	0.3	0.7	0.0	0.0	0.7	0.3	0.0	0.0	0.0	0.0	0.0
Elphidium gerthi	1.7	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
Elphidium albiumbilicatum	0.0	1.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.0
Elphidium williamsoni	0.7	1.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.3
Elphidium selseyense	2.3	2.7	2.3	3.0	3.3	5.3	3.3	4.7	3.7	4.0	5.3	4.7	5.0	7.3	6.0	24.0	25.7	23.0	8.0	6.7
Cibicides lobatulus	4.0	5.0	4.3	0.0	0.3	0.3	0.0	0.7	0.7	1.7	0.7	1.3	0.0	0.0	3.0	0.0	0.0	0.3	2.7	4.7
Nonionella turgida	2.3	2.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.0	0.3	1.3	0.0	0.0	0.3	1.7	0.3
Adercotytryma glomeratume	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0
Haynesina germanica	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Uvigirina perigrina	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0

FORAMINIFERA- DOWN-CORE RELATIVE ABUNDANCES -CORE (SC-02-A)

Species	*0-1 cm*	*1-2 cm*	*2-3 cm*	*3-4 cm*	*4-5 cm*	*5-6 cm*	*6-7 cm*	*7-8 cm*	*8-9 cm*	*9-10 cm*	*10-11 cm*	*11-12 cm*	*12-13 cm*	*13-14 cm*
Reophax scotti	0.6	0.6	3	3	0	0	0	0	0	0	0	0	0	0
Reophax scorpiurus	0.3	0.9	0.9	1.3	0.3	0.3	0	0.6	1	1.2	0.6	0.3	0.6	1.3
Haplophragmoides bradyi	0.9	0.9	0.9	1.3	0	0.3	0.3	0.3	0.3	0	0	0	0.3	0.3
Ammoscalaria runiana	19.8	28.2	31.5	35.9	34.3	39	1	16	23	21	21	31	22	25.4
Textularia bocki	0	0	0	0	0	0	1	2.7	3.3	3	4.2	6	6.6	5.2
Eggerella scabra	38.5	38.2	39	36.3	35.9	30	31	25	19	18.9	22	16	18.7	15.4
Lagena striata	1.2	0	0	0	0	0	0	0	0	0.6	0.3	0	0	0.3
Stainforthia loeblochi	0.6	0	0	0	0	0	0	0.3	0	0.3	0.3	0	0.6	0
Oolina williamsoni	0	0	0	0	0.3	0.6	0	0	0	0	0.3	0	0.6	0.6
Bolivina pseudoplicata	0	0	0	0	0	0	0	0.3	0	0.3	0.3	0.3	0.6	0.3
Bulimina elongata	0.3	0.3	0.3	0.6	0.9	1	1.3	1	1.6	1.5	1	2.6	0.3	0
Bulimina marginata	7.6	2.7	4.5	2.3	3.1	4.6	4.6	5.6	7	6.9	3	2	3.6	4.9
Asterigerinata mamilla	1.8	1.3	0.6	0	0	1	1.3	2.3	1.3	1.2	0.6	0.6	1.9	0.6
Ammonia beccarii	25.3	21.9	17.2	18.4	19.6	20	30	34	37	29.6	36	35	35	34.4
Elphidium aculeatum	0	0	0	0	0.3	0	0	0.3	0.6	0.3	1	0.3	0	0.9
Elphidium selseyense	2.1	1.3	3	2.6	2.5	1.3	1	5.3	2.6	3.4	1.3	3.6	4.6	4.2
Cibicides lobatulus	0	0	0	0	0	0	0	1	1	1.8	2.6	3.6	2.6	2.9
Nonionella turgida	0	0	0	0	0	0	0	0	0	1.2	0.6	0.3	0.3	0.3

FORAMINIFERA- DOWN-CORE RELATIVE ABUNDANCES -CORE (SC-04-B)

Species	*0-1 cm*	*1-2 cm*	*2-3 cm*	*3-4 cm*	*4-5 cm*	*5-6 cm*	*6-7 cm*	*7-8 cm*	*8-9 cm*	*9-10 cm*	*10-11 cm*
Reophax scorpiurus	1.1	0.4	0.8	1.3	1.3	1.5	0.8	1.3	2.9	1.5	1.2
Haplophragmoides bradyi	0	0.8	0.4	0.4	0.4	0	0.4	0.4	0	0.3	0
Ammoscalaria runiana	20.2	17.2	22	21.7	23.1	17.4	21.4	23.6	21.4	19.3	22.8
Textularia bocki	1.4	0.8	2.5	2.6	3.1	2.2	4.7	9	7.1	3.8	3.6
Eggerella scabra	28.9	25.2	20.7	14.2	15.5	16	16.7	11.3	12.1	14.6	15
Lagena striata	0	0.4	0	0	0	0.3	0.4	0	0	0	0
Stainforthia loeblichi	0	0	0.4	0	0	0	0.4	0.4	0.8	0.3	0
Oolina williamsoni	1.1	0.4	0.8	1.3	0.8	0.3	0.8	1.3	1.2	1.1	0.8
Fisssurina elliptica	0.5	0.4	0	0	0	0.3	1.2	0.9	0.8	1.5	0.4
Fissurina lucida	0.2	0.8	0.4	0.4	0.4	0	0	0.4	0	0	0
Bolivina pseudoplicata	0.2	0	0	0	0.4	0.6	0	0	0.4	1.5	0.4
Bolivina skagerrakeniss	0	0	0	0	0	0.3	1.7	0.4	0.4	0.7	0.8
Bulimina elongata	0.8	2.3	1.6	1.3	2.6	0	0.4	0.4	1.6	1.1	0.4
Bulimina marginata	12	12.1	8.8	7.1	7.1	4.7	5.5	5	4.6	4.6	2.4
Asterigerinata mamilla	0.5	2.3	0	3.5	2.2	1.9	1.2	2.2	2.9	1.5	1.2
Ammonia beccarii	25.4	27.4	31.7	38.6	39.1	38	36.4	36.3	34.4	35.9	35.5
Elphidium aculeatum	0.2	0.4	0.4	1.3	0	0.9	0	1.8	0	1.5	0.4
Elphidium margaratecium	0.2	0.4	0	0	0	0	0.8	0.4	1.2	0	0
Elphidium selseyense	1.7	7	6.3	2.2	3.1	1.9	3	4.5	2.9	3.8	6.9
Cibicides lobatulus	1.1	0.8	2.1	1.3	3.1	1.5	2.1	2.2	2.1	4.2	2
Nonionella turgida	0.2	0.4	0.8	0.4	0	0	0	0.4	0	0	0

APPENDIX 2 - ENVIRONMENTAL VARIABLES

ORGANIC MATTER (OM) DATA

SURFACE SEDIMENT OM DATA – (CHAPTER 4).

BEFORE AFTER

	Drying									%	
ID	M0 (g)	M0 (g)	Ms (g)	M250 (g)	M550 (g)	PI	PII	Rp	Labile OM	Refractory OM	Total OM
CC-01-A	14.97	14.95	0.98	14.93	14.88	0.02	0.06	0.71	2.26	5.63	7.88
CC-01-B	13.52	13.51	0.98	13.49	13.44	0.02	0.05	0.71	2.01	5.02	7.04
CC-01-C	13.81	13.79	0.98	13.77	13.72	0.02	0.05	0.73	1.83	4.90	6.73
CC-02-A	13.22	13.20	0.98	13.16	13.11	0.04	0.05	0.57	3.63	4.82	8.45
CC-02-B	13.60	13.57	0.98	13.54	13.49	0.03	0.05	0.59	3.44	4.97	8.40
SC-02-A	13.62	13.60	0.97	13.56	13.51	0.04	0.05	0.57	4.08	5.37	9.45
CS-03-A	14.59	14.58	0.99	14.55	14.51	0.03	0.04	0.56	2.99	3.82	6.82
CC-03-B	14.47	14.46	0.99	14.44	14.40	0.03	0.04	0.59	2.61	3.78	6.40
CC-03-C	14.56	14.55	0.98	14.52	14.48	0.03	0.04	0.57	2.83	3.79	6.63
SC-03-A	13.15	13.14	0.99	13.11	13.07	0.03	0.04	0.59	2.66	3.84	6.50
SC-04-A	14.70	14.69	0.99	14.67	14.63	0.02	0.04	0.61	2.43	3.78	6.21
SC-04-B	14.47	14.45	0.99	14.43	14.39	0.03	0.04	0.59	2.72	3.91	6.63
SC-05-A	13.48	13.47	0.99	13.45	13.40	0.02	0.05	0.72	1.86	4.69	6.55
SC-06-A	13.46	13.44	0.99	13.41	13.35	0.03	0.06	0.64	3.33	5.93	9.26
SC-07-A	13.84	13.83	0.98	13.81	13.76	0.02	0.05	0.68	2.27	4.83	7.10
SC-08-A	14.44	14.43	0.99	14.41	14.37	0.02	0.04	0.71	1.74	4.20	5.94

CONTINUED- SURFACE SEDIMENT OM DATA

STATIONS	*SEDIMENT CORE-ID*	*%TC*	*%OC*	*%IC*	*%N*	*%H*	*%S*	*OC/N*	*%TOM*
STATION 01	CC-01-A	2.95	2.85	0.1	0.19	0.62	0.59	17.5	6.73
STATION 02	SC-02-A	4.73	3.94	0.79	0.4	0.98	0.71	11.49	9.45
STATION 03	SC-03-A	3.8	2.73	1.07	0.19	0.59	0.37	16.76	6.5
STATION 04	SC-04-B	3.09	2.87	0.22	0.42	0.58	0.59	7.97	6.63
STATION 05	SC-05-A	2.57	1.9	0.67	0.24	0.61	0.33	9.24	6.55
STATION 06	SC-06-A	5.73	4.46	1.27	0.3	0.77	0.48	17.34	9.26
STATION 07	SC-07-A	2.89	2.69	0.2	0.19	0.57	0.31	16.52	7.1
STATION 08	SC-08-A	2.24	1.66	0.58	0.14	0.55	0.2	13.83	5.94
STATION 09	GB-03-C	8.02	4.18686	3.83314	0.42	1.867	0.606	11.63	-
STATION 10	GB-07-A	7.21	5.11016	2.09984	0.44	1.554	0.535	13.55	-
STATION 11	GB-09-A	7.04	4.62348	2.41652	0.5	1.573	0.269	10.79	-
STATION 12	GB-20-A	6.25	1.89504	4.35496	0.15	0.628	0.201	14.7392	-
STATION 13	GB-28-A	2.32	0.98366	1.33634	0.11	0.476	0.166	10.4328	-

DOWN-CORE SEDIMENT DATA (CHAPTER 3 AND 5).

CORE- SC-02-A

			DRYING								%		
CORE ID CORE	**Core Depth (cm)**	**Sample Size (g)**	**Crucible (g)**	**M_0 (g)**	**M_0 (g)**	**M_s (g)**	**M_{250} (g)**	**M_{550} (g)**	**PI**	**PII**	**Rp**	**Labile OM**	**Refractory OM**	**Total OM**
SC-02-A	2	0.9964	13.9699	14.9663	14.9332	0.9633	14.9092	14.8435	0.024	0.0657	0.73	2.49	6.82	9.31
	3	1.003	12.5264	13.5294	13.4997	0.9733	13.4719	13.4221	0.0278	0.0498	0.64	2.86	5.12	7.97
	4	0.999	12.8076	13.8066	13.7746	0.967	13.7409	13.6763	0.0337	0.0646	0.66	3.49	6.68	10.17
	5	1.0009	12.2125	13.2134	13.1877	0.9752	13.1557	13.1101	0.032	0.0456	0.59	3.28	4.68	7.96
	6	1	12.5934	13.5934	13.5663	0.9729	13.5436	13.4993	0.0227	0.0443	0.66	2.33	4.55	6.89
	7	0.9976	12.6276	13.6252	13.6021	0.9745	13.5758	13.5351	0.0263	0.0407	0.61	2.70	4.18	6.88
	8	1.005	13.5921	14.5971	14.5766	0.9845	14.5494	14.5111	0.0272	0.0383	0.58	2.76	3.89	6.65
	9	0.9908	13.4699	14.4607	14.4417	0.9718	14.4216	14.3844	0.0201	0.0372	0.65	2.07	3.83	5.90
	10	1.0036	13.7009	14.7045	14.6859	0.985	14.6628	14.6252	0.0231	0.0376	0.62	2.35	3.82	6.16
	11	0.9961	13.5791	14.5752	14.5591	0.98	14.5382	14.4992	0.0209	0.039	0.65	2.13	3.98	6.11
	12	0.9929	11.5292	12.5221	12.5066	0.9774	12.4864	12.4475	0.0202	0.0389	0.66	2.07	3.98	6.05
	13	1.0009	10.0817	11.0826	11.0658	0.9841	11.0475	11.0034	0.0183	0.0441	0.71	1.86	4.48	6.34

CORE- SC-03-A

CORE ID CODE	CORE DEPTH (CM)	SAMPLE SIZE (G)	CRUCIBLE (G)	M_0 (G)	M_0 (G)	M_S (G)	M_{250} (G)	M_{550} (G)	PI	PII	RP	LABILE OM	REFRACTORY OM	TOTAL OM
SC-03-A	2	0.9973	13.9698	14.9671	14.9465	0.9767	14.9278	14.8901	0.0187	0.0377	0.67	1.91	3.86	5.77
	3	1.0024	12.5267	13.5291	13.5099	0.9832	13.4927	13.4514	0.0172	0.0413	0.71	1.75	4.20	5.95
	4	0.9959	12.8079	13.8038	13.7846	0.9767	13.7639	13.7239	0.0207	0.04	0.66	2.12	4.10	6.21
	5	1.0038	12.2128	13.2166	13.1982	0.9854	13.1799	13.1374	0.0183	0.0425	0.70	1.86	4.31	6.17
	6	1.004	12.5929	13.5969	13.5784	0.9855	13.5606	13.5175	0.0178	0.0431	0.71	1.81	4.37	6.18
	7	0.999	12.6282	13.6272	13.6092	0.981	13.5947	13.5504	0.0145	0.0443	0.75	1.48	4.52	5.99
	8	1.0068	13.5925	14.5993	14.5831	0.9906	14.5677	14.5309	0.0154	0.0368	0.70	1.55	3.71	5.27
	9	1.0038	13.4708	14.4746	14.4584	0.9876	14.4436	14.4067	0.0148	0.0369	0.71	1.50	3.74	5.23
	10	0.9925	13.5693	14.5618	14.5445	0.9752	14.5291	14.4892	0.0154	0.0399	0.72	1.58	4.09	5.67
	11	1.0012	13.7022	14.7034	14.6872	0.985	14.6731	14.6351	0.0141	0.038	0.73	1.43	3.86	5.29
	12	0.9994	12.1464	13.1458	13.1305	0.9841	13.1178	13.0813	0.0127	0.0365	0.74	1.29	3.71	5.00
	13	1.0044	13.4617	14.4661	14.4516	0.9899	14.4406	14.4071	0.011	0.0335	0.75	1.11	3.38	4.50
	14	1.0036	12.4811	13.4847	13.4751	0.994	13.4621	13.4152	0.013	0.0469	0.78	1.31	4.72	6.03

CORE- SC-04-B

				DRYING									%	
CORE ID CODE	**Core Depth (cm)**	**Sample Size (g)**	**Crucible (g)**	**M_0 (g)**	**M_0 (g)**	**M_s (g)**	**M_{250} (g)**	**M_{550} (g)**	**PI**	**PII**	**Rp**	**Labile OM**	**Refractory OM**	**Total OM**
SC-04-B	2	1.0023	13.9704	14.9727	14.9529	0.9825	14.9403	14.8951	0.0126	0.0452	0.78	1.28	4.6	5.88
	3	0.9997	12.5272	13.5269	13.5076	0.9804	13.4932	13.4479	0.0144	0.0453	0.76	1.47	4.62	6.09
	4	0.9946	12.8085	13.8031	13.7844	0.9759	13.7682	13.7268	0.0162	0.0414	0.72	1.66	4.24	5.9
	5	0.9998	12.2134	13.2132	13.1953	0.9819	13.1813	13.1385	0.014	0.0428	0.75	1.43	4.36	5.78
	6	1.0057	12.5939	13.5996	13.5829	0.989	13.5739	13.5307	0.009	0.0432	0.83	0.91	4.37	5.28
	7	0.9937	12.6286	13.6223	13.6069	0.9783	13.5975	13.5579	0.0094	0.0396	0.81	0.96	4.05	5.01
	8	1.004	13.5932	14.5972	14.5811	0.9879	14.5675	14.5284	0.0136	0.0391	0.74	1.38	3.96	5.33
	9	1.0003	13.4715	14.4718	14.4555	0.984	14.4423	14.4025	0.0132	0.0398	0.75	1.34	4.04	5.39
	10	1.0093	13.5701	14.5794	14.5659	0.9958	14.5546	14.5205	0.0113	0.0341	0.75	1.13	3.42	4.56
	11	0.9977	12.1459	13.1436	13.1302	0.9843	13.1186	13.0828	0.0116	0.0358	0.76	1.18	3.64	4.82
	12	0.9997	13.7018	14.7015	14.6882	0.9864	14.6769	14.6376	0.0113	0.0393	0.78	1.15	3.98	5.13
	13	1.0013	13.4611	14.4624	14.4461	0.985	14.4336	14.3905	0.0125	0.0431	0.78	1.27	4.38	5.64
	14	1.0003	12.4808	13.4811	13.4668	0.986	13.4533	13.4114	0.0135	0.0419	0.76	1.37	4.25	5.62

CORE- SC-05-A

				BEFORE Drying	AFTER Drying								%	
CORE ID CODE	Core Depth (cm)	Sample Size (g)	Crucible (g)	M_0 (g)	M_0 (g)	M_s (g)	M_{250} (g)	M_{550} (g)	PI	PII	Rp	Labile OM	Refractory OM	Total OM
SC-05-A	2	1.0057	12.4508	13.4565	13.4405	0.9897	13.4171	13.3737	0.0234	0.0434	0.65	2.36	4.39	6.75
	3	1.0019	12.8445	13.8464	13.8271	0.9826	13.8039	13.7598	0.0232	0.0441	0.66	2.36	4.49	6.85
	4	1.0082	13.4409	14.4491	14.4333	0.9924	14.4121	14.3696	0.0212	0.0425	0.67	2.14	4.28	6.42
	5	0.9999	13.2952	14.2951	14.2812	0.986	14.2637	14.2256	0.0175	0.0381	0.69	1.77	3.86	5.64
	6	1.005	12.1937	13.1987	13.1871	0.9934	13.1708	13.1343	0.0163	0.0365	0.69	1.64	3.67	5.32
	7	1.0019	12.5236	13.5255	13.5141	0.9905	13.5036	13.4653	0.0105	0.0383	0.78	1.06	3.87	4.93
	8	0.9955	13.5798	14.5753	14.5629	0.9831	14.5525	14.5171	0.0104	0.0354	0.77	1.06	3.60	4.66
	9	0.9964	10.6481	11.6445	11.6332	0.9851	11.6233	11.5829	0.0099	0.0404	0.80	1.00	4.10	5.11
	10	1.0066	10.8127	11.8193	11.8081	0.9954	11.7962	11.7584	0.0119	0.0378	0.76	1.20	3.80	4.99
	11	0.9988	10.7553	11.7541	11.7421	0.9868	11.7322	11.6916	0.0099	0.0406	0.80	1.00	4.11	5.12
	12	1.0064	10.7927	11.7991	11.7867	0.994	11.7764	11.7355	0.0103	0.0409	0.80	1.04	4.11	5.15

CORE- SC-06-A

				BEFORE Drying	AFTER Drying								%	
CORE ID CODE	Core Depth (cm)	Sample Size (g)	Crucible (g)	M_0 (g)	M_0 (g)	M_s (g)	M_{250} (g)	M_{550} (g)	PI	PII	Rp	Labile OM	Refractory OM	Total OM
SC-06-A	2	0.9996	13.9707	14.9703	14.9464	0.9757	14.9155	14.8605	0.0309	0.055	0.64	3.17	5.64	8.80
	3	0.9968	12.5273	13.5241	13.5022	0.9749	13.4719	13.4201	0.0303	0.0518	0.63	3.11	5.31	8.42
	4	0.9971	12.8101	13.8072	13.7863	0.9762	13.7557	13.7086	0.0306	0.0471	0.61	3.13	4.82	7.96
	5	1.0011	12.2142	13.2153	13.1962	0.982	13.1744	13.1363	0.0218	0.0381	0.64	2.22	3.88	6.10
	6	0.9978	12.5944	13.5922	13.5739	0.9795	13.5537	13.5146	0.0202	0.0391	0.66	2.06	3.99	6.05
	7	0.9999	12.6302	13.6301	13.6146	0.9844	13.5975	13.5625	0.0171	0.035	0.67	1.74	3.56	5.29
	8	1.0003	13.5936	14.5939	14.5789	0.9853	14.5652	14.5298	0.0137	0.0354	0.72	1.39	3.59	4.98
	9	1.0047	13.4722	14.4769	14.4633	0.9911	14.4511	14.4173	0.0122	0.0338	0.73	1.23	3.41	4.64
	10	1.001	13.5703	14.5713	14.5582	0.9879	14.5461	14.5098	0.0121	0.0363	0.75	1.22	3.67	4.90
	11	1.0015	12.1468	13.1483	13.1355	0.9887	13.1242	13.0894	0.0113	0.0348	0.75	1.14	3.52	4.66
	12	1.0051	13.7028	14.7079	14.6966	0.9938	14.6851	14.6504	0.0115	0.0347	0.75	1.16	3.49	4.65
	13	1.0022	13.4625	14.4647	14.4551	0.9926	14.4416	14.4069	0.0135	0.0347	0.72	1.36	3.50	4.86

CORE-SC-07-A

				BEFORE Drying	AFTER Drying								%	
CORE ID CODE	Core Depth (cm)	Sample Size (g)	Crucible (g)	M_0 (g)	M_0 (g)	M_s (g)	M_{250} (g)	M_{550} (g)	PI	PII	Rp	Labile OM	Refractory OM	Total OM
SC-07-A	2	0.9982	12.8444	13.8426	13.8245	0.9801	13.8034	13.7541	0.0211	0.0493	0.70	2.15	5.03	7.18
	3	0.9975	13.4426	14.4401	14.4201	0.9775	14.3991	14.3524	0.021	0.0467	0.69	2.15	4.78	6.93
	4	0.9987	13.2957	14.2944	14.2771	0.9814	14.2587	14.2115	0.0184	0.0472	0.72	1.87	4.81	6.68
	5	0.9988	12.1944	13.1932	13.1764	0.982	13.1573	13.1094	0.0191	0.0479	0.71	1.95	4.88	6.82
	6	0.9966	12.5237	13.5203	13.5048	0.9811	13.4937	13.4449	0.0111	0.0488	0.81	1.13	4.97	6.11
	7	0.9947	13.5798	14.5745	14.5601	0.9803	14.5505	14.4989	0.0096	0.0516	0.84	0.98	5.26	6.24
	8	0.9988	10.7553	11.7541	11.7391	0.9838	11.7289	11.6814	0.0102	0.0475	0.82	1.04	4.83	5.87
	9	0.9924	10.6481	11.6405	11.6252	0.9771	11.6168	11.5667	0.0084	0.0501	0.86	0.86	5.13	5.99
	10	0.998	10.7928	11.7908	11.7767	0.9839	11.7702	11.7229	0.0065	0.0473	0.88	0.66	4.81	5.47
	11	0.9973	10.8133	11.8106	11.7979	0.9846	11.7903	11.7424	0.0076	0.0479	0.86	0.77	4.86	5.64
	12	0.9916	13.9691	14.9607	14.9425	0.9734	14.9381	14.8933	0.0044	0.0448	0.91	0.45	4.60	5.05
	13	1.0032	12.5256	13.5288	13.5104	0.9848	13.5076	13.4637	0.0028	0.0439	0.94	0.28	4.46	4.74

CORE- SC-08-A

				BEFORE Drying	AFTER Drying								%	
CORE ID CODE	Core Depth (cm)	Sample Size (g)	Crucible (g)	M_0 (g)	M_0 (g)	M_s (g)	M_{250} (g)	M_{550} (g)	PI	PII	Rp	Labile OM	Refractory OM	Total OM
SC-08-A	2	0.9989	12.4528	13.4517	13.4306	0.9778	13.4166	13.3719	0.014	0.0447	0.76	1.43	4.57	6.00
	3	0.9954	12.8455	13.8409	13.8243	0.9788	13.8102	13.7667	0.0141	0.0435	0.76	1.44	4.44	5.88
	4	1.0015	13.4416	14.4431	14.4286	0.987	14.4155	14.3766	0.0131	0.0389	0.75	1.33	3.94	5.27
	5	0.9951	13.2962	14.2913	14.2741	0.9779	14.2619	14.2197	0.0122	0.0422	0.78	1.25	4.32	5.56
	6	0.9981	12.1946	13.1927	13.1799	0.9853	13.1673	13.1289	0.0126	0.0384	0.75	1.28	3.90	5.18
	7	1.0026	12.5245	13.5271	13.5159	0.9914	13.5022	13.4618	0.0137	0.0404	0.75	1.38	4.08	5.46
	8	1.0084	13.5809	14.5893	14.5757	0.9948	14.5594	14.5168	0.0163	0.0426	0.72	1.64	4.28	5.92
	9	0.9948	10.6477	11.6425	11.6288	0.9811	11.6117	11.5641	0.0171	0.0476	0.74	1.74	4.85	6.59
	10	1.0002	10.8139	11.8141	11.8009	0.987	11.7841	11.7359	0.0168	0.0482	0.74	1.70	4.88	6.59

GRAIN SIZE ANALYSIS

Sample ID code	*Latitude, N*	*Longitude, W*	*Depth [m]*	*% Clay*	*% Silt*	*% Sand*	*Mean/Median ratio*	*Skewness*	*Kurtosis*
CC-01-A	56° 31.141	5° 22.386	37	20.7	46.4	32.8	1.568	4.52	29.61
CC-01-B	56° 31.134	5° 22.299	37	20	44.7	35	2.052	3.619	14.62
CC-01-C	56° 31.133	5° 22.298	38	19	43.1	37.7	1.571	2.55	7.963
CC-02-A	56° 31.372	5° 21.434	27.2	18.4	45	36.5	1.842	3.14	12.5
CC-02-B	56° 31.372	5° 21.437	29.9	17.6	43.5	38.7	1.928	2.872	10.15
SC-02-A	56° 31.373	5° 21.436	30	16.5	44.6	38.8	1.559	2.607	9.267
SC-03-A	56° 31.377	5° 21.466	29.2	13	42	44.9	1.574	3.912	20.32
CC-03-A	56° 31.376	5° 21.465	29	13.6	41.6	44.8	1.903	3.086	10.99
CC-03-B	56° 31.375	5° 21.464	29	13.7	42.3	43.8	1.66	3.318	14.43
SC-04-A	56° 31.368	5° 21.475	29.8	14.3	42.6	42.8	1.5	2.819	9.627
SC-04-B	56° 31.370	5° 21.478	29.7	14.5	42.7	42.8	1.546	3.985	23.26
SC-05-A	56° 31.359	5° 21.565	30.1	19.2	49.5	31.2	1.497	3.013	11.33
SC-06-A	56° 31.486	5° 21.167	27.4	15.1	47	37.7	1.88	4.464	25.2
SC-07-A	56° 31.483	5° 21.147	24.8	16.9	52.9	30.1	1.478	2.942	10.54
SC-08-A	56° 31.520	5° 21.065	23	16.1	57.7	26.1	1.43	3.55	16.35
GB-03-C	56' 33.188	5’15.130	12.5	7.35	86.45	6.18	1.554	2.89	10.59
GB-07-A	56' 33.010	5 15.072	13.72	7.55	86.05	6.38	1.59	1.58	2.31
GB-09-A	56' 32.937	5 15.549	22.7	8.84	86.99	4.17	1.646	2.12	5.13
GB-20-A	56' 31.430	5 20.220	17.6	8.32	52.08	19.6	2.05	4.88	31.69
GB-28-A	56' 31.293	5 22.694	29.6	6.22	48.71	45.07	1.3	2.175	8.36

BOTTOM WATER DISSOLVED OXYGEN (DO2) DATA

Dissolved O_2

Date	Time (HH:MM:SS)	Time (s)	Comment	Oxygen Ch1	Compensation Ch 1	Temp. Probe ('C)	Raw Data: Ch 1	Signal Ch1	Ambient Ch1
31/05/2016	10:28:46	0	**Station 1**	257.69	10.621	10.621	24.085	13.626	6.386
31/05/2016	10:28:51	5		260.12	11.81	11.81	23.504	13.218	6.236
31/05/2016	10:28:56	10		262.67	12.992	12.992	22.92	12.803	6.109
31/05/2016	10:29:01	15		263.43	12.854	12.854	22.938	12.814	6.127
31/05/2016	10:29:06	20		263.72	12.823	12.823	22.937	12.808	6.13
31/05/2016	10:29:11	25		264.92	12.841	12.841	22.878	12.802	6.158
31/05/2016	10:29:16	30		263.5	12.868	12.868	22.931	12.81	6.15
31/05/2016	10:29:21	35		262.29	12.897	12.897	22.974	12.822	6.156
31/05/2016	10:29:26	40		261.99	12.906	12.906	22.983	12.834	6.123
31/05/2016	10:29:31	45		262.96	12.907	12.907	22.94	12.821	6.123
31/05/2016	10:29:36	50		263.49	12.91	12.91	22.915	12.806	6.089
31/05/2016	10:29:41	55		262.75	12.925	12.925	22.942	12.805	6.1
31/05/2016	10:29:46	60		262.82	12.931	12.931	22.936	12.806	6.088

Dissolved O_2

				Oxygen	Compensation	Temp. Probe	Raw Data:	Signal	Ambient
31/05/2016	10:29:59	73.03	**Station 2**	253.48	13.531	13.531	23.155	12.98	6.348
31/05/2016	10:30:04	78.03		244.52	13.91	13.91	23.435	13.139	6.416
31/05/2016	10:30:09	83.03		238.22	13.977	13.977	23.701	13.318	6.542
31/05/2016	10:30:14	88.03		243.82	13.17	13.17	23.733	13.321	6.411
31/05/2016	10:30:19	93.03		251.15	12.399	12.399	23.677	13.322	6.459
31/05/2016	10:30:24	98.03		255.77	11.834	11.834	23.678	13.321	6.506
31/05/2016	10:30:29	103.03		259.56	11.46	11.46	23.649	13.327	6.546
31/05/2016	10:30:34	108.03		261.76	11.218	11.218	23.644	13.329	6.505
31/05/2016	10:30:39	113.03		263.11	11.065	11.065	23.643	13.328	6.509
31/05/2016	10:30:44	118.03		264.73	10.967	10.967	23.61	13.32	6.525
31/05/2016	10:30:49	123.03		264.46	10.901	10.901	23.648	13.325	6.612
31/05/2016	10:30:54	128.03		265.84	10.85	10.85	23.606	13.332	6.637
31/05/2016	10:30:59	133.03		266.01	10.819	10.819	23.612	13.327	6.627

Dissolved O_2

				Oxygen	Compensation	Temp. Probe	Raw Data:	Signal	Ambient
31/05/2016	10:31:07	140.95	**Station 3**	263.45	10.983	10.983	23.664	13.391	6.642
31/05/2016	10:31:09	143.03		258.34	11.243	11.243	23.794	13.447	6.627
31/05/2016	10:31:14	148.03		252.27	11.627	11.627	23.922	13.524	6.65
31/05/2016	10:31:19	153.03		250.51	11.858	11.858	23.913	13.521	6.656
31/05/2016	10:31:24	158.03		250.14	11.996	11.996	23.877	13.514	6.618
31/05/2016	10:31:29	163.03		250.19	12.002	12.002	23.872	13.512	6.576
31/05/2016	10:31:34	168.03		250.03	11.965	11.965	23.894	13.513	6.468
31/05/2016	10:31:39	173.03		249.36	11.931	11.931	23.939	13.502	6.32
31/05/2016	10:31:44	178.03		249.38	11.903	11.903	23.949	13.498	6.312
31/05/2016	10:31:49	183.03		249.17	11.882	11.882	23.966	13.49	6.348
31/05/2016	10:31:54	188.03		249.85	11.877	11.877	23.936	13.488	6.474
31/05/2016	10:31:59	193.03		250.68	11.886	11.886	23.893	13.483	6.48
31/05/2016	10:32:04	198.03		251.31	11.902	11.902	23.857	13.472	6.5
31/05/2016	10:32:09	203.03		251.48	11.905	11.905	23.848	13.466	6.464

Dissolved O_2

				Oxygen	Compensation	Temp. Probe	Raw Data:	Signal	Ambient
31/05/2016	10:32:18	211.62	**Station 4**	250.21	12.105	12.105	23.831	13.41	6.305
31/05/2016	10:32:19	213.03		249.64	12.269	12.269	23.794	13.366	6.182
31/05/2016	10:32:24	218.03		250.96	12.257	12.257	23.737	13.326	6.032
31/05/2016	10:32:29	223.03		254.17	11.891	11.891	23.729	13.32	5.99
31/05/2016	10:32:34	228.03		258.02	11.465	11.465	23.718	13.325	5.908
31/05/2016	10:32:39	233.03		260.19	11.154	11.154	23.74	13.317	5.842
31/05/2016	10:32:44	238.03		262.17	10.967	10.967	23.725	13.315	5.787
31/05/2016	10:32:49	243.03		263.05	10.849	10.849	23.732	13.307	5.705
31/05/2016	10:32:54	248.03		263.18	10.779	10.779	23.754	13.321	5.721
31/05/2016	10:32:59	253.03		263.09	10.729	10.729	23.777	13.326	5.696
31/05/2016	10:33:04	258.03		262.35	10.691	10.691	23.826	13.342	5.727
31/05/2016	10:33:09	263.03		263.17	10.666	10.666	23.799	13.34	5.767
31/05/2016	10:33:14	268.03		263.91	10.645	10.645	23.774	13.359	6.204
31/05/2016	10:33:19	273.03		265.01	10.64	10.64	23.727	13.366	6.707

Dissolved O_2

				Oxygen	Compensation	Temp. Probe	Raw Data:	Signal	Ambient
31/05/2016	10:33:36	289.94	**Station 5**	263.83	11.128	11.128	23.589	13.324	7.01
31/05/2016	10:33:41	294.94		261.22	11.673	11.673	23.493	13.28	7.013
31/05/2016	10:33:46	299.94		258.12	12.181	12.181	23.434	13.245	6.958
31/05/2016	10:33:51	304.94		258.01	12.193	12.193	23.434	13.265	7.047
31/05/2016	10:33:56	309.94		258.33	12.133	12.133	23.444	13.271	7.04
31/05/2016	10:34:01	314.94		259.38	12.095	12.095	23.41	13.277	6.908
31/05/2016	10:34:06	319.94		258.38	12.067	12.067	23.466	13.272	6.826
31/05/2016	10:34:11	324.94		258.11	12.052	12.052	23.484	13.27	6.775
31/05/2016	10:34:16	329.94		257.42	12.041	12.041	23.52	13.261	6.882
31/05/2016	10:34:21	334.94		258.12	12.035	12.035	23.491	13.258	6.884
31/05/2016	10:34:26	339.94		258.15	12.021	12.021	23.495	13.255	6.882
31/05/2016	10:34:31	344.94		258.36	12.015	12.015	23.488	13.256	6.809
31/05/2016	10:34:36	349.94		258.39	12.004	12.004	23.49	13.259	6.828

Dissolved O_2

				Oxygen	Compensation	Temp. Probe	Raw Data:	Signal	Ambient
31/05/2016	10:34:46	359.36	**Station 6**	255.87	12.21	12.21	23.527	13.32	6.877
31/05/2016	10:34:46	359.95		252.42	12.424	12.424	23.606	13.373	6.979
31/05/2016	10:34:51	364.94		249.25	12.601	12.601	23.685	13.43	7.087
31/05/2016	10:34:56	369.94		249.62	12.524	12.524	23.697	13.423	7.155
31/05/2016	10:35:01	374.94		250.99	12.379	12.379	23.688	13.424	7.215
31/05/2016	10:35:06	379.94		251.94	12.238	12.238	23.698	13.425	7.194
31/05/2016	10:35:11	384.94		252.96	12.127	12.127	23.694	13.427	7.196
31/05/2016	10:35:16	389.94		254.19	12.044	12.044	23.668	13.424	7.095
31/05/2016	10:35:21	394.94		255.01	11.992	11.992	23.65	13.418	6.969
31/05/2016	10:35:26	399.94		254.97	11.938	11.938	23.673	13.414	6.915
31/05/2016	10:35:31	404.94		255.03	11.919	11.919	23.678	13.411	6.923
31/05/2016	10:35:36	409.94		254.91	11.893	11.893	23.693	13.407	6.991
31/05/2016	10:35:41	414.94		254.38	11.887	11.887	23.72	13.401	6.869
31/05/2016	10:35:46	419.94		254.53	11.875	11.875	23.718	13.402	6.762

Dissolved O_2

				Oxygen	Compensation	Temp. Probe	Raw Data:	Signal	Ambient
31/05/2016	10:36:00	433.67	**Station** 7	252.69	11.97	11.97	23.767	13.427	6.863
31/05/2016	10:36:05	438.67		251.27	11.988	11.988	23.827	13.47	6.992
31/05/2016	10:36:10	443.67		249.29	11.94	11.94	23.938	13.509	7.179
31/05/2016	10:36:15	448.67		250.75	11.712	11.712	23.959	13.529	7.142
31/05/2016	10:36:20	453.67		252.23	11.527	11.527	23.961	13.534	7.098
31/05/2016	10:36:25	458.67		253.5	11.366	11.366	23.965	13.53	6.789
31/05/2016	10:36:30	463.67		253.92	11.259	11.259	23.988	13.534	6.728
31/05/2016	10:36:35	468.67		254.21	11.19	11.19	24.001	13.52	6.482
31/05/2016	10:36:40	473.67		254.6	11.147	11.147	24	13.51	6.446
31/05/2016	10:36:45	478.67		255.4	11.128	11.128	23.971	13.491	6.399
31/05/2016	10:36:50	483.67		256.49	11.104	11.104	23.93	13.489	6.589
31/05/2016	10:36:55	488.67		257.55	11.107	11.107	23.88	13.498	6.82
31/05/2016	10:37:00	493.67		257.16	11.125	11.125	23.891	13.506	6.846

Dissolved O_2

				Oxygen	Compensation	Temp. Probe	Raw Data:	Signal	Ambient
31/05/2016	10:37:13	506.64	**Station 8**	252.9	11.408	11.408	23.981	13.565	6.873
31/05/2016	10:37:18	511.64		248.81	11.591	11.591	24.101	13.642	6.987
31/05/2016	10:37:23	516.64		246.52	11.62	11.62	24.198	13.725	7.124
31/05/2016	10:37:28	521.64		248.03	11.273	11.273	24.262	13.739	7.117
31/05/2016	10:37:33	526.64		249.9	10.961	10.961	24.296	13.735	6.949
31/05/2016	10:37:38	531.64		249.99	10.745	10.745	24.377	13.722	6.798
31/05/2016	10:37:43	536.64		250.69	10.619	10.619	24.395	13.732	6.776
31/05/2016	10:37:48	541.64		250.86	10.529	10.529	24.423	13.734	6.8
31/05/2016	10:37:53	546.64		253.09	10.477	10.477	24.339	13.742	6.756
31/05/2016	10:37:58	551.64		254.42	10.437	10.437	24.293	13.726	6.772
31/05/2016	10:38:03	556.64		255.57	10.414	10.414	24.248	13.732	6.835
31/05/2016	10:38:08	561.64		254.02	10.394	10.394	24.328	13.719	6.832
31/05/2016	10:38:13	566.64		253.2	10.389	10.389	24.369	13.719	6.84