THE UNIVERSITY OF HULL

IMPLICATIONS OF THE NATURE AND QUALITY OF DREDGED MATERIAL AND ITS BENEFICIAL PLACEMENT IN THE COASTAL ENVIRONMENT

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by

ELAINE MITCHELL BSc (HONS) HULL

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Abstract:

Dredged sediment is increasingly being used in mudflat recharge schemes and in habitat restoration/recreation to counter the effect of erosion and sea-level rise. For this reason it is necessary to determine the response of indigenous mudflat fauna to anthropogenic sediment deposition and so in 2001 a manipulative experimental laboratory study was used to assess the biological response to the alternative beneficial use of uncontaminated maintenance dredged material. The experiment assessed the response of common temperate macro-benthic organisms to the addition of increasing amounts of simulated dredged material on to the surface of mudflat cores. Between 0 cm and 20 cm of defaunated sediment was added as both high and low frequency treatments and the vertical migration of species per 1 cm or 3 cm sediment increment was determined. The experiment showed that the bivalve *Macoma balthica* (Linnaeus) was able to vertically migrate into the surface layers of low or high depositions of sediment treatments but the Spionid polychaete *Pygospio elegans* (Claparède) and nematodes were less able to reach the surface layers with increased sediment deposition. The oligochaete *Tubificoides benedii* (Udekem) ability to vertically migrating into larger low frequency depositions of fine-grained sediment treatment placements was less when compared to coarser sand treatments. Hence the study showed that specific errant macro-zoobenthic species vertically migrated through increasing depths of sediment overburden.

This concept was investigated further in the winter of 2001 as manipulative experimental field studies at the Skeffling mudflats along the Humber Estuary and included an investigation to assess the biological response to increased depositions of simulated dredged material at the high-shore area. The main focus of these studies was to understand the relationship between the amounts of fine-grained simulated dredged material deposition and macro-faunal re-colonization through vertical and lateral migration. Defaunated sediment treatments were added as single low frequency amounts of 27 cm and 50 cm and the ability of macro-invertebrate species to migrate to a natural position within the vertical profile of the manipulated sediment was assessed. The re-colonization of defaunated fine-grained sediment via the below surface horizontal migration of macro-fauna occurred when 27 cm of sediment was deposited and the main colonizers were *M. balthica*, juvenile Tellinacea and *T. benedii*. The macro-faunal re-colonization of a 50 cm deposition of defaunated fine-grained material occurred within 6 weeks via vertical migration. The main vertical migration colonizers were *M. balthica*, juvenile Tellinacea and *T. benedii*. The deposition of a single large amount of fine-grained sediment had a detrimental affect on macro-faunal nematode re-colonization.

Further experimental investigations concerning the impact of burial following the high-frequency depositions of simulated fine-grained dredged material on a temperate intertidal mudflat community during the spring-summer period were carried out during 2002 and 2003. Additionally, the logistics of dredged material deposition at different tidal heights was investigated. This was achieved by examining the responses of key mudflat macro-fauna to burial by manipulated water content of fine-grained sediment treatments deposited at the upper-, high- and mid-shore areas of an estuarine intertidal mudflat and determining the macro-faunal re-colonization potential via settlement from the water column. *Tubificoides benedii* demonstrated a high ability to colonize an increased sediment water content treatment throughout the experiment when deposited at the high- and mid-shore areas but colonized the upper-shore sediment treatment from the middle to end period of the experiment. The polychaete *Hediste diversicolor* (O.F. Müller), in particular the juvenile stage demonstrated a good ability to colonize the upper-shore fine-grained sediment treatment. The high-shore early treatment colonizers included *T. benedii* and nematodes, other species colonized the treatment microcosms from July onwards; *T. benedii*, *H. diversicolor*, the Spionid polychaete *Streblospio shrubsolii* (Buchanan) and the gastropod *Hydrobia ulvae* (Pennant) and *M. balthica* throughout the experiment. At the mid-shore the early colonizers included *T. benedii*, *M. balthica*, *P. elegans* and *S. shrubsolii*. The colonization ability of *M. balthica*, juvenile Tellinacea and *H. ulvae* were negatively correlated to an increase in sediment water content especially when deposited at the high-shore. *Tubificoides benendii* was the only species to show a sediment-associated pattern at the high-shore and was positively correlated to the sediment water content of the treatments. When simulated fine-grained dredged material was deposited as small multiple amounts over time, the mudflat height was slowly recharged and allowed to build up, this allowed the gradual macro-faunal re-colonization of the recharge material over time. In general, the deposition of manipulated water content fine-grained sediment treatments did not inhibit macro-faunal recovery. This information may be used during the decision making process upon the feasibility of the alternative beneficial uses of dredged material such as when determining the type of dredged material used during a sediment recharge scheme or during simulated dredged material deposition studies.

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1 Introduction

1.1 Coastal management: Flood and coastal defence

The coastal areas of the UK have many uses, such as commercial fisheries; sediment extraction, nature reserves, recreational areas and the users include shipping companies, fishing vessels and the commercial dredging industry. This has led to a number of controlling and interested parties when coastal management is considered (French, 1997). In England the Department of Environment, Fisheries, and Rural Affairs (DEFRA) is the main flood and coastal defence authority (PIANC, 1992) and produces flood and coastal defence programmes to reduce the risks of coastal erosion, encroachment and flooding to people and/or the land. The Environment Agency (EA) is the main operating authority and is responsible for safety and environmental sustainability.

For management, long pieces of coastline have become divided into smaller sediment cells, each with an individual local-scale management strategy. Within an area of coastline, several regional management plans can be linked to form a broader scheme. Such links allow for a better understanding of trans-boundary processes, for example, a detrimental effect may be experienced further along the coast as a result of hard engineering defences in a particular area (DEFRA, 2000) and amplifies the exacerbation of a retreating of salt marshes (Kirby, 1996). When a 'hold the line' coastal defence approach is taken, intertidal habitats become increasingly vulnerable to impacts such as 'coastal squeeze' (Jones, 2001). 'Coastal squeeze' can be defined as the progressive loss of salt marsh area due to the construction of flood defences, where the transgression of salt marsh in response to sea-level rise is interrupted and the inner marshes are unable to transgress as the outer marshes continue to erode (IECS, 1992). Consequently, the salt marsh becomes squeezed between hard sea defences and a rising sea level (Fletcher, *et al.*, 2001). 'Coastal squeeze' could become more damaging than the direct increase of sea-level rise; for example, during the past 70 years the Severn Estuary experienced 3 m of tidal flat lowering (Kirby, 1996). This loss of habitat has implications to fisheries, waterfowl and wading birds (Fletcher, *et al.*, 2001). All coastal management plans are used as a base for a national coastal defence strategy and a holistic approach is used within Coastal Zone Management (CZM) or Integrated Coastal Zone Management (ICZM) (French, 1997). More recently, DEFRA set into practice, a series of mechanisms to ensure the flood and coastal defence, approach and policy were being delivered in conjunction with legislative requirements, following the Agriculture Select Committee 1998 and Shoreline Management Plans (SMP's) are promoted by DEFRA to achieve targets by adopting a holistic approach to plan coastal defence development within a coastal sediment cell (DEFRA, 2001). Targets were set in place to implement SMP's by 2001, within England, Coastal Habitat Management Plans (CHaMP's) are developed to protect areas of SPAs and SACs within coastal sediment cells where flood and coastal defence schemes are taking place (DEFRA, 2001).

1.2 Beneficial use of dredged material

In the past dredged material was regarded as a waste and therefore needed to be discarded with minimum impact. The introduction of landfill tax within UK legislation increased the cost of dredged material disposal at landfill sites and so alternative methods were sought. Consequently, sea disposal was chosen as a favourable alternative route to land disposal and was considered practicable in both environmental and economical terms. During the 1980s, however, dredged material was re-categorised from a waste to one of a potential resource (Kirby, 1996) and the possibility of utilising uncontaminated dredged material as a resource set the direction towards the implementation of many categories of alternative uses; the focus being beneficial uses (PIANC, 1992; IADC/CEDA, 1999).

As sea levels are rising, with a predicted range of 15 to 95 cm over the next century (Cecconi, 1997), the impact on the UK shoreline is becoming more severe and the destabilisation of many flood defences is becoming a problem. Many coastal habitats such as intertidal mudflats, salt marshes, beaches and areas with coastal vegetation act as efficient absorbers of wave energy (EA, 2000) and therefore have an influential role within erosional processes. There are two main factors responsible for natural salt marsh degradation, sea-level rise and subsequent marsh submersion (Delaney, *et al.*, 2000). Only those salt marshes capable of compensating for rising sea levels by trapping sediments and retaining marsh organic matter may develop and survive submersion (Cecconi, 1997). The degradation of salt marshes along the low lying east coast of the UK may lead to changes with possible detrimental effects to conservation, navigation or sea defences (ABP, 1998). In the UK the salt marsh and mudflat areas of the southeast are eroding at a rate of approximately 40 ha yr^{-1} (Hughes and Paramor, 2004).

The Oslo-Paris Commission (1998) (OSPAR) and the Dredged Material Assessment Framework (DMAF) (1996) of the London Convention (1972) (LC72) guidelines used for the management of dredged material disposal recommend the beneficial use of dredged material as an alternative to sea disposal. As an example of this, fine-grained uncontaminated maintenance dredged material is now used beneficially as a habitat remediation tool in coastal protection and hence beach nourishment is considered as part of a holistic approach to solving the problem of coastal erosion (Dixon and Pilkey, 1991). Similarly, a second new coastal management method uses managed realignment to counter the effect of erosion and sea-level rise (French, 2006) whereby the managed retreat of a muddy coastal area can be used to combat erosion by developing a buffer zone following the setback of coastal defences onto low-value land (Kirby, 1996). This form of coastal protection was carried out at Tollesbury and Orplands in Essex (Kirby, 1996; IADC/CEDA, 1999; Widdows, *et al.*, 2006), along the Tees Estuary (Evans, *et al.*, 1998) and at various locations along the Humber Estuary including Paull Holme Strays (EA, 2005; Mazik, 2006; Mazik, *et al.*, 2007), Welwick and Alkborough, where existing sea defence walls were deliberately breached to allow tidal inundation, mudflat development and salt marsh succession (Elliott, *et al.*, 2000). The timing of flooding is an important consideration in order to facilitate the benthic invertebrate colonization of the created mudflat (Evans, *et al.*, 1998).

Beach nourishment is now common practice (Dixon and Pilkey, 1991; Kadomastsu and Fujiuara, 1991; Foster, *et al.*, 1996; Essink, 1997) and especially within the UK for the recharge of eroding estuarine intertidal mudflat areas (ABP, 1998; Posford Duviver, 1998; Casella – The Environment Group, 1998; Elliott, *et al.*, 2000). It is particularly important that recharge schemes at least maintain intertidal habitat integrity and if possible enhance the high carrying capacity of estuaries for fish and migratory birds (Posford Duvivier, 1998; PIANC, 1992; McLusky and Elliott, 2004). Hence, uncontaminated fine-grained dredged material can be used as a resource to raise, replenish or encourage the stabilisation of intertidal mudflats (PIANC, 1992; DEFRA, 2000). Following the recharge of a mudflat profile however, the material will take time to consolidate (Elliott, *et al.*, 2000) and may delay mechanisms for recovery of the estuarine intertidal fauna and so it is important to determine these recovery processes and the response of the primary estuarine prey organisms (Bolam and Whomersley, 2003).

1.2.1 Beach nourishment

The restoration of many beaches depleted by erosion are replenished during a beneficial use scheme by the direct recharging of an area, with sediment of a similar particle grain size to that of the receiving environment, to artificially maintain the shore profile. The implementation of this soft engineering coastal protection technique is achieved by placing material directly onto an area or by spray/pumping material from an offshore rainbow dredger (Elliott, *et al.*, 2000) and is now common practice on a world-wide scale, for example, areas in: the Gulf of Mexico (Dixon and Pilkey, 1991), Tobon coast, Japan (Kadomastsu and Fujiuara 1991), Mt. Maunganui beach, New Zealand (Foster, *et al.*, 1996) and the Risk Analysis of Coastal Nourishment (RIACON) sites in Denmark, Germany, The Netherlands, Belgium and Spain (Essink, 1997). Beach nourishment within the UK has now been implemented at Trimley marshes, Suffolk (Posford Duviver, 1998), Hunstanton/Heacham, East Anglian coast (Casella – The Environment Group, 1998) and the Lincolnshire coast, (Elliott, *et al.*, 2000).

In the past, the recharging of beaches for recreational use occurred at major coastal tourist resorts. More recently, the practice of beach nourishment is considered as a workable tool, using a holistic approach to solving the problem of coastal erosion (Dixon and Pilkey, 1991) and is now primarily used to protect an eroding coastline. The direct placement of dredged material onto an eroding beach or foreshore area is thought to equilibrate erosion-deposition processes by providing a replacement for the sediment lost. Consequently, further erosion is reduced or prevented, thus the overall protection of the land behind is achieved. Beach nourishment is considered a feasible and natural form of beach protection by way of restoring, protecting and/or extending a depleted intertidal area (van Oorschot and van Raalte, 1991). Beach replenishment can be achieved from near shore disposal, where across-shore sediment transport processes disperse the dredged material onto the area (Foster, *et al.*, 1996). Hard engineering defences such as groynes and breakwaters are often used to help stabilise the formation of a new beach.

1.2.2 Wetland creation/restoration

The most severe coastal erosion and flooding incidents usually occur on low-lying areas of the south and east coasts of England, such areas are subsiding, leading to further problems with increasing relative sea level. The remaining areas of the UK coastline have steeper slopes and are predominately made up of a rocky substratum, resulting in an abundance of coves and bays where small beaches may develop. The use of uncontaminated fine-grained maintenance dredged material for wetland creation, restoration or managed retreat of the intertidal area or its recharge is technically practicable and widespread within the UK (PIANC, 1992). Eroding or subsiding wetland shorelines are stabilised following the placement of dredged material for example, by increasing the intertidal elevation to match that of surrounding areas. Ford, *et al.*, (1999) noted a subsiding coastal wetland area was restored when recharged to a depth of 23 mm. In some cases a greater sediment grain size may be used to prevent dispersal to areas away from the recharge site, similarly the cohesiveness of the dredged material may be increased (French, 1997) through a dewatering process (Glindermann, 1996; Ishikawa, 2001).

Streever (2000) provides a review of several cases of salt marsh creation or restoration taking place over three decades in the USA, where natural and created marshes were compared in Galveston Bay, Texas (Delaney, *et al.*, 2000; Shafer and Streever, 2000) and PIANC (1992) describe a site in South Louisiana. Wetland creation can be used to develop a new habitat; an example is an intertidal dredged spoil island created using sandy dredged material in North Florida (Subrahmanyam, 1984). Subsequently, the benthic invertebrate colonization and succession of the created area occurred, including the utilization by fish and birds. Streever (2000) suggested that both differences and similarities occur between fine-grained dredged material created salt marshes and natural salt marshes based on various attributes. For example, geomorphology (Delaney, *et al.*, 2000; Shafer and Streever, 2000), plant communities (Fulford, 1994; Posey, *et al.*, 1997; Alphin and Posey, 2000), fish utilization of benthos (Minello and Zimmerman, 1992; Minello and Webb, 1997), benthic invertebrates (LaSalle, *et al.*, 1991; Moy and Levin, 1991; Minello and Webb, 1997; Posey, *et al.*, 1997; Alphin and Posey, 2000) and birds (Melvin and Webb, 1998).

1.2.2.1 Adjustment of the intertidal mudflat profile using fine-grained dredged material

Habitat creation is thought to enhance coastal wetlands and improve the near-shore fishery (PIANC, 1992) and is therefore considered beneficial to both society and wildlife. During the construction process, other resources are often utilized in addition to dredged material. Beach replenishment techniques are predominately used for the restoration of sandy beach areas, many replenishment schemes are now used for the recharge of eroding estuarine intertidal mudflat areas. Currently less than 1 % of approximately 40 million wet tonnes of dredged material annually produced in the UK is used beneficially (Bolam, *et al.*, 2003a).

Many estuaries provide a rich benthic food source for fish and migratory birds (Posford Duvivier, 1998; PIANC, 1992), which rely on the primary food source to fuel long migratory patterns. Uncontaminated fine-grained dredged material is used to restore or enhance specific areas within an estuary such as important vegetation, biological, or bird habitats. Therefore, the restoration and recovery of impacted intertidal areas are more beneficial than the creation of a new aquatic habitat that could result in the replacement of one habitat type with another (PIANC, 1992). The main goal of an intertidal beneficial use scheme is to improve the carrying capacity for fish and bird predation (Bolam, *et al.*, 2006). At present in the UK, many 'beneficial use' schemes are limited to small-scale trials in the intertidal zone of the estuarine environment (Bolam and Whomersley, 2003), such as at the Westwick Marina along the Crouch Estuary (Bolam, 2000b; Bolam and Whomersley, 2003; Widdows, *et al.*, 2006). Other sites include the Titchmarsh Marina (Bolam and Whomersley, 2005; Widdows, *et al.*, 2006), North Shotley (Elliott, *et al.*, 2000; Bolam and Whomersley, 2005), Horsey Island, Pewit Island and Trimley marshes (ABP, 1998), the Maldon salt marsh, Blackwater Estuary, where fine-grained material was used to mitigate the depleted salt marsh (Dearnaley, *et al.*, 1995; IADC/CEDA 1999; Widdows, *et al.*, 2006) and the Parkstone Marina, Poole harbour (Dearnaley, *et al.*, 1995). Subtidal schemes include Naze North, Essex and the Blackwater Estuary (ABP, 1998). The majority of dredged material beneficial use schemes have taken place in the USA and have mostly been developed by the US Army Corps of Engineers (USACE). Yozzo, *et al.*, (2004) describe schemes within the New York – New Jersey districts and Costa-Pierce and Weinstein (2002) provide a summary of USACE beneficial use projects. Several studies aimed at the effects of the disposal of dredged material in open waters have been carried out. For example, in a South Carolina estuary, USA (Van Dolah, *et al.*, 1984); in the Anse à Beaufils, Baie des Chaleurs, Eastern Canada (Harvey, *et al.*, 1998); on a shallow water soft-sediment community in the Solitary Islands Marine Park, NSW, Australia (Smith and Rule, 2001); in the Charleston Ocean (Zimmerman, *et al.*, 2003); a near shore disposal area off the coast of Louisiana, USA (Flemer, *et al.*, 1997). Also, a sublittoral disposal area included an experimental dredged material disposal site in Mecklenburg Bay, western Baltic Sea (Powilleit, *et al.*, 2006). Additionally, Cruz-Motta and Collins (2004) studied the short- and long-term effects of the disposal of uncontaminated dredged material on the macro-zoobenthos.

Erosional processes exacerbated by rising sea levels and the direct development on to the intertidal are two main impacts responsible for the degradation of intertidal habitats (Kirby, 1996). Two methods are used to achieve the replenishment of the intertidal such as by spray/pumping a one-off placement or several layers of dredged material directly on to the foreshore or secondly by slowly enhancing an area by trickle-charging natural process, using mounds to disperse the material. Each method has its advantages and disadvantages; for example, the latter method has less impact on the benthic community, although the required profile would take longer to achieve (PIANC, 1992).

1.2.2.2 Onshore feeding

If the managed retreat of an eroding mudflat is not possible, a self-sustaining management technique is favoured. The adjustment of an intertidal mudflat profile using an onshore feeding method of disposal are described by HR Wallingford (Burt, 1996) and can be combined with a realignment of the shoreline to advance mudflats and are often used when an eroding foreshore is backed by high-value land (Kirby, 1996). Alternatively, the direct placement of material onto the foreshore can take place. For example, the disposal of maintenance dredged material using a thin-layer technique (developed in the USA) used a jet-spray to disperse sediment in the Venice lagoon during a partial restoration project and was undertaken to counteract erosion and submersion by re-creating 3.31 km^2 of marsh (Cecconi, 1997; Ford, *et al.*, 1999). These techniques would achieve a new mudflat height, or reach a level of elevation similar to that experienced previously in an area and is particularly important in areas of severe erosion. The recharge of an area can act as a preventative measure in areas of stable mudflats.

With sediment cell maintenance and coastal protection schemes, the overall environmental benefit of newly deposited dredged material may temporarily be reduced, as potential impacts of the direct placement of dredged material may have detrimental effects on marine resources such as the biological properties of a mudflat (IADC/CEDA, 1999). Such problems may be further exacerbated by the dispersal of dredged material to surrounding areas and will be dependent on the hydrodynamic regime of an area (IADC/CEDA, 1998). As a temporary or permanent measure, the recharge is often retained by a confinement structure such as a bund or a dike; this helps prevent sediment moving to other areas (Elliott, *et al.*, 2000). A confinement structure encourages the stabilisation of the material and protects the created habitat from erosion (Fulford, *et al.*, 1994). For example, the short-term dispersion of maintenance dredged material and macro-invertebrate response was monitored at a site behind a breakwater in the Delaware Bay, USA (Leathem, *et al.*, 1973). Additionally, confinement structures were used to help construct intertidal mudflats at Jonesport, Maine, USA (Ray, 2000). Similarly, direct successive deposition events can occur to achieve salt marsh creation, for example, created marshes in Carolina, USA (Alphin and Posey, 2000). However, as fine-grained dredged material is often transported as a fluid produced during the dredging and disposal processes and could give reason for concern (Kirby, 1996), especially in sloping areas where gravity may move the material down the shore. Shoreline protection techniques can be combined with sediment stabilisation. For example, an intertidal area of directly disposed maintenance dredged material in Galveston Bay, Texas, USA was stabilised by wetland vegetation planting (Minello, 2000) and a relocation site at Pot-Nets, Delaware, USA, was stabilised by planting and protected by offshore stone breakwaters (Fulford and Tunnell, 1994) and the effect of wave action at the marsh edged was reduced by the construction of a wooden pole boundary (Cecconi, 1997).

1.2.2.3 Trickle charging

The trickle charging of dredged material disposal is aimed at achieving a similar objective to that of onshore feeding. The adjustment of an intertidal mudflat profile would be difficult to achieve using this method, as the dredged material is deposited in small quantities, offshore in an area close to the recharge site and dispersed using natural process. However, trickle charging has been comparable to a sustainable natural process and was implemented at an accretionary area in the Medway Estuary, Kent (Kirby, 1996). Similarly, fine-grained maintenance dredged material was used to construct offshore berms in Mobile Bay, the Gulf of Mexico (Dredging Research Technical Notes, 1992: in Kirby, 1996), which dispersed the material onto the mudflat using natural forces. Artificial structures such as mound and berms often act as congregation areas for fish (PIANC, 1992) and thereby provide temporary shelter. The offshore soft berm also acts as an efficient absorber of wave energy (Dearnaley, *et al.*, 1995). Therefore, the wave climate impinging on the shoreline would become modified (PIANC, 1992; Kirby, 1996; IADC/CEDA, 1999) and shoreline stability could be achieved. If the berm is positioned correctly, i.e. in an area of small tidal currents with low to moderate wave activity (Kirby, 1996), a decrease in the erosion potential of a mudflat will be experienced, resulting in an increase of mudflat stability. Erosion potential experienced at the edge of salt marshes within an estuary would also become less severe. This method has good potential however, as a beneficial use it would not be suitable for areas of extreme tidal conditions, as the deposit would be eroded and dispersed to other places. The timing of disposal is therefore crucial, especially when trickle charging as the operational period takes considerably longer and the dispersal site may become subject to adverse weather conditions that may disperse the material to areas away from the recharge site. Under normal climatic conditions, both methods used to recharge intertidal areas retain the deposited material within the same cell system.

1.2.2.4 Constraints on uncontaminated fine-grained dredged material as an alternative beneficial use

The use of fine-grained material from most maintenance dredging in coastal protection projects is limited due to the nature of the physical properties such as the consolidation properties and unpredictable dispersal patterns in the marine environment. Therefore, the physical parameters of the dredged material such as the re-colonization potential, consolidation, size, consistency and contamination levels, dictate the best suitable use of fine-grained material for habitat creation/enhancement and intertidal recharge schemes within the estuarine environment. Following the recharge of a mudflat profile, the material will take time to consolidate (Elliott, *et al.,* 2000) and may delay recovery mechanisms. The best available method of delivery for a scheme must be considered in order to keep the costs down. For example, the use of a cutter section dredger will transport the dredged material through a pipeline to the recharge site. Constraints are often experienced when searching for a suitable location for an intertidal recharge site within an estuary, for example, by land ownership, coastal development or the location of existing intakes and outfalls. It is therefore important that all schemes are designed following an in depth investigation of all variables likely to be affected and that the evaluation of the overall value of an alternative beneficial use, be discussed by representatives of all bodies concerned (see appendices for the criteria used during the licensing process). For example, in Essex, the EA have developed Flood Protection Schemes, which use dredged material transported from Felixstowe and Harwich ports (ABP, 1998; DEFRA, 2000).

1.2.2.5 The consequences of burial; Biological impacts and sediment modification

The responses of benthic communities during beneficial use schemes are being investigated; this will provide a valuable source of information, as currently there is limited knowledge (Bolam, *et al.*, 2006). The deposition of dredged material can directly affect the sediment composition of the receiving environment or indirectly cause irreversible changes to abiotic variables such as local current patterns, topography, sediment sulphide concentrations, the redox state, pH value and increased areas of oxygen deficiency.

1.3 Aims and objectives

The overall aim of the research is to provide experimental evidence concerning the impact of burial following the deposition of simulated dredged material on an estuarine intertidal macro-zoobenthic community, by examining the responses of benthic populations to physical perturbations. This information may be used during the decision making process upon the feasibility of the alternative beneficial uses of dredged material. The specific objectives of this research and hypotheses are given in each chapter.

A total of 5 experimental designs were developed during the project, aimed at providing a better understanding of biological, physical and logistical factors affecting the recovery of processes of beneficial use schemes. These experiments investigated the nature of simulated dredged material such as particle size, organic content and water content of sediment. Additionally, the logistical factors were considered at the study site, such as the timing, tidal height placement, amount and frequency of sediment deposition. These factors were manipulated and mudflat macro-faunal re-colonization of manipulated sediments was determined. Recovery of a mudflat community could take place by three possible mechanisms: i) vertical migration up into the deposited sediment overburden by fauna present within the mudflat below, ii) horizontal migration of macro-fauna from adjacent mudflat areas and iii) settlement of macro-fauna from the water column.

The main objectives of these studies were to suggest which species are able to withstand burial:

- of up to 20 cm of simulated dredged material when deposited as a single amount or smaller multiple amounts and are able to vertically migrate to a natural position within the sediment profile during a laboratory-based microcosm study (chapter 2);
- of 50 cm fine-grained simulated dredged material when deposited as a single amount and are able to vertically migrate to a natural position within the vertical profile of the defaunated sediment treatment during a field microcosm study (chapter 3);
- of 27 cm fine-grained simulated dredged material when deposited as a single amount and are able to horizontally migrate to a natural position within the vertical profile of the defaunated sediment treatment during a field microcosm study (chapter 3);
- of up to 14 cm manipulated water content of fine-grained sediment treatment when deposited as a single amount or smaller multiple amounts and are able to colonize the sediment microcosms via settlement from the water column during a field microcosm study (chapter 4);
- of up to 10 cm manipulated water content of fine-grained sediment when deposited as a single amount or smaller multiple amounts and are able to colonize the sediment microcosms via settlement from the water column during a field microcosm study (chapter 5).

1.4 Study area: Humber Estuary

The Humber Estuary is a large funnel-shaped estuary situated along the northeast coast of England (Figure 1.1) and is one of the UK's largest estuaries. The tidal length of the Humber stretches approximately 120 km and the name Humber is used for the first 62 km until the confluence of the Rivers Trent and Ouse at Trent Falls (Barr, *et al.,* 1990), whilst the mouth of the Humber has a width of 15 km (Pethick, 1988). The catchment areas, covers one fifth of England and is inhabited by approximately ten million people. The estuary receives waste from domestic, industrial and agricultural sources.

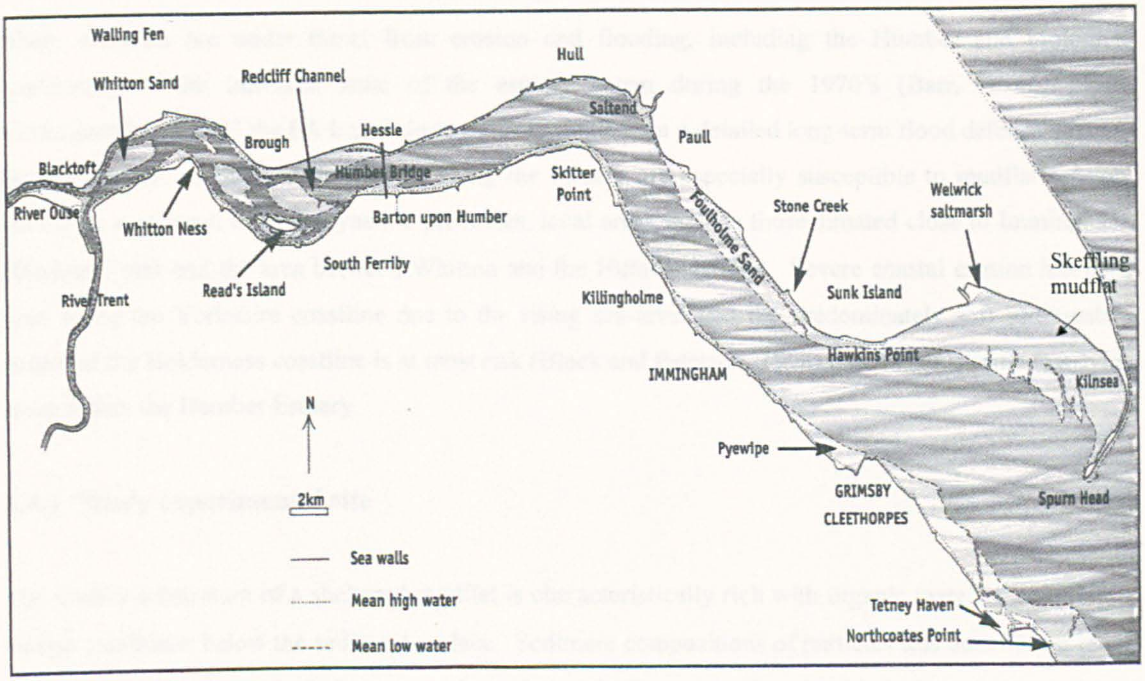


Figure 1.1: The Humber Estuary.

The Humber Estuary has a macro-tidal range of 7.2 m thus tidal forces predominate. At high water, the deepest channel depth can reach 18 m and the rapidly rising flood tide can take two to three hours to rise as it moves towards the head of the estuary. Consequently, this has strong implications on the currents within the channel, as powerful inland currents are created simultaneously (Pethick, 1988). The ebb tide however is much slower and takes approximately nine hours to fall, current velocities are considerably less than those experienced during a flood tide, allowing the sediment particles to settle out of the water column (Pethick, 1988). The Humber Estuary has 3 million tonnes of sediment suspended in the water column on each tide and approximately 6 million tonnes of sediment enters the estuary each year (Pethick, 1988). The two main sources of marine sedimentary input are background material derived from the North Sea and erosion of the Holderness coast (EA, 1999). In addition, 200 000 tonnes of sediment enters the estuary via a fluvial route (Pethick, 1988) but the majority of sedimentary input returns to the North Sea on the next ebb tide, although some of the material is retained in the estuary and later accumulates when driven upstream or enters the many channels present within the estuary. Due to the nature of the bathymetry, wide mudflats and salt marshes occur mostly on the north bank. Erosion and accretion does occur during natural processes such as the summer-winter erosion and deposition cycles. The principal cause of erosion between Whitton and the Humber Bridge takes place during a period of channel switching. During this cycle erosion takes place on both shores of the inner estuary as the channel moves from one side to the other (EA, 2000). The estuary is generally well mixed, but due to the effects of the Coriolis force a horizontal halocline exists across the estuary (Barr, *et al.*, 1990; Pethick, 1990; Allen, *et al.*, 1996). This forces freshwater flows towards the southern bank, whilst the saline intrusion is directed along the northern bank, both affecting the amount and position of sediment concentrations within the water column. The Humber Bridge is approximately 45 km inland and is the place where the saline intrusion reaches a limit and much of the sediment tends to concentrate (Pethick, 1988).

Many estuaries are under threat from erosion and flooding, including the Humber and biological monitoring of the intertidal zone of the estuary began during the 1970's (Barr, *et al.*, 1990). Consequently, in 1997 the EA began discussions to implement a detailed long-term flood defence strategy for the estuary. Several areas situated along the estuary are especially susceptible to mudflat erosion, occurring as a result of hydrodynamic processes, local areas include those situated close to Immingham, Hawkins Point and the area between Whitton and the Humber Bridge. Severe coastal erosion has been seen along the Yorkshire coastline due to the rising sea-level and the predominately soft sedimentary nature of the Holderness coastline is at most risk (Black and Paterson, 1998) and includes some low-lying areas within the Humber Estuary.

1.4.1 Study experimental site

The muddy substratum of a sheltered mudflat is characteristically rich with organic material, resulting in anoxic conditions below the sediment surface. Sediment compositions of particles less then 63 μm id are held together by electrostatic forces and form flocs. Particles less than 2 μm id are cohesive and bind sediment together. A high surface water content and low permeability with increasing depth are similarly typical. Many organisms contribute to the process of binding of sediment particles. For example, diatoms produce extra-cellular mucoid substances and the production of faecal pellets of bioturbating polychaetes and snails involves enclosing fine particles within a mucoid envelope. Cohesiveness allows organisms to form and maintain burrows in the sediment.

The binding of sediment particles plays an important role during the erosion-deposition process and can be demonstrated by comparing the settling rates of different sized particles in water; in one hour a 5 μm particle would fall approximately 7 cm and a 500 μm particle would fall 1800 cm. The high-shore mudflats are relatively stable due to the cohesive properties of finer sediments, making this type of substrata more resistant to erosion. The sedimentary regime is greatly influenced by an overall equilibrium between hydrodynamic forces such as wave action and the tidal regime. If the equilibrium state changes as a result of a sedimentary disturbance, a general disruption to the benthic community will be experienced, with possible irrevocable effects and as the critical velocity is reached sediments begin to break up and erode. Secondly, a change in sediment supply can have a direct affect on erosional-depositional processes within an area and changes in sediment composition, erosion or accretion may occur.

The intertidal zone of Spurn Bight is approximately 56 km^2; this area is enclosed by Spurn spit on the north shore of the Humber Estuary (Black and Paterson, 1997). The predominant areas of salt marsh are located along the north bank, towards the mouth of the estuary. The present investigations were situated on the northeast bank of the Humber Estuary. Access to the field site was gained from the village of Skeffling, approximately 1 mile from the village are the sea defences and a pumping station, beyond this point is the Skeffling marsh (Plate 1.1). The marsh is relatively (approximately 60 to 80 m wide), there is a well-developed creek system consisting of water-filled runnels (< 1 m wide) present from the middle to lower marsh area, beyond that are an area of extensive mudflats. The Skeffling mudflats (Figure 1.1) were chosen as the experimental field site mainly because of the ease of accessibility, species richness, sediment surface area and degree of exposure and flow dynamics. Skeffling mudflats are located at the following co-ordinates: 53 °N 38.577, 000 °E 04.073 (or grid reference: 194 372 (Landranger Map No. 113 Grimsby and surrounding area)).

Plate 1.1: Skeffling salt marsh and mudflats.

1.4.1.1 Characteristics of the field site

There is a clear zonation within the salt marsh community, the dominant species are *Puccinellia maritima* (Hudson) and *Atriplex portulacoides* (Linnaeus) and are interspersed by *Spartina anglica* (Hubbard), *Salicornia europaea* (Linnaeus), *Suaeda maritima* (Linnaeus), *Aster tripolium* (Linnaeus) and *Spergularia spp*., (Armstrong, *et al.,* 1985; Brown, 1998). *Spartina* patches (approximately 0.4 to 2 m) were present in areas of the lower marsh section including the marsh edge and bare mudflat (Brown, 1998) which were subjected to scouring and consequently surrounded by depressions containing standing water (Armstrong, *et al.,* 1985) (Plate 1.2).

Plate 1.2: *Spartina* patch, Skeffling marsh edge. (Arrow indicates a *Spatina* patch in a mudflat depression)

The Skeffling mudflat is approximately 4 km wide and has a slope of 1:1000 (Black and Paterson, 1998). Dyer, *et al.*, (2000) provides a classification of the intertidal mudflats at Skeffling. A number of ridges and runnels occur within the creek system approximately 500 m from the shore (de Deckere, *et al.,* 2001). At the Skeffling flats, the distribution of fine inorganic particle size from the mean high-water mark (MHWM) to the mid high-water mark (MMWM) along a transect perpendicular to the shoreline was mostly uniform. However an increase in sand content was evident towards the low-shore area (3000 m from the high-shore) (Black and Paterson, 1998). The organic carbon content and onshore fining of inorganic particle size along a transect next to the pumping station, increased towards the upper-shore (Black and Paterson, 1998). Widdows, *et al.,* (2000) noted a seasonal change of percentage particulate organic matter in sediment, from 3.9 % during the summer to 6.2 % in the winter, at a site on the high-shore. Also, trends in bulk density at the mudflat varied temporally, changes were attributed to periods of severe weather conditions that caused the mudflat surface to scour and secondly, to the heterogeneous nature of particle size distribution which may promote compaction (Black and Paterson, 1998). However, Widdows, *et al.,* (2000) concluded that bulk density at two sites of the high-shore at the Skeffling mudflat were similar temporally. For example, wet bulk density ranged between 1.48 and 1.56g cm^{-3} during the summers of 1996/7 and 1.54 g cm^{-3} in October 1996. The sediment stability of the mudflat was greatest at the high-shore area (Widdows, *et al.,* 2000), although some erosion occurred during the highest spring tides (Black, 1998) and the low levels of erosion at the high-shore were related to increased exposure and low densities of the bivalve *Macoma balthica* (Linnaeus).

1.5 Indicator species

Macro-fauna are defined as between 500 µm to 5 cm including polychaetes, crustacea, molluscs and oligochaetes and meio-fauna are between 63 to 500 µm including nematodes. Within such divisions, species can then be segregated into infaunal species, those that reside within the sediment and epifaunal species, which occur mainly upon the sediment surface. Benthic macro-invertebrates have a wide range of characteristics, which make them suitable for sediment manipulation studies, including density, size, abundance, ecotrophic functional group (including trophic status, feeding guild, the role of an organism within an assemblage and an indication of motility) and collection accessibility (Maurer, *et al.*, 1980-81). Specific benthic macro-faunal species are used as bio-monitors of biological responses to impacts, by recording changes in species presence and/or abundance (Elliott, *et al.*, 1998) and bio-indicators have been used during burial manipulation experiments in the field (Bolam, 2000c, 2003; Bolam and Fernandes, 2003). The present studies included species typical of a temperate estuarine mudflat including benthic epifauna and infauna (Table 1.1) and include the mollusc *Hydrobia ulvae* (Pennant) a near surface dwelling gastropod occurring in the top 3 cm. Maximum densities of *H. ulvae* are found on the surface or in the top 1.5 cm of sediment (Huxham, *et al.*, 1995), this species are often present in organically rich sediments. Juvenile *M. balthica* (300 µm in size) settle at the low intertidal area during May, and then migrate up to the high intertidal area, until the on set of winter when migration occurs back to the low intertidal. Temporally, *M. balthica*, the polychaetes *Eteone longa/flava* agg (Fabricius) and *Hediste diversicolor* (O.F. Müller) and oligochaetes were the most abundant taxa within an intertidal mudflat study located at the Skeffling mudflats (Ratcliffe, 1979; Sharpless, 2000). In other studies at the field site, different species were recorded (Table 1.2) and Sharpless (2000) and de Deckere, *et al.*, (2001) recorded the presence of the polychaete *Streblospio shrubsolii* (Buchanan).

Table 1.1: Description of the main macro-faunal species at the Skeffling mudflats.

Species	Description
Hydrobia ulvae	A near surface small, estuarine gastropod mollusc, grazes on benthic diatoms. Favouring the intertidal mudflats and muddy-sand, abundant above mid-tidal level but sublittoral to 20 m.
Retusa obtusa	Small opisthobranch mollusc, feeds on *H. ulvae*. Located in sand, muddy-sand and mud of the lower intertidal to about 50 m.
Abra tenuis	Sub-triangular Tellinid bivalve mollusc. Found in soft substrata in estuaries and intertidal flats.
Macoma balthica	Broadly oval-shaped Tellinid bivalve mollusc. Located in estuarine intertidal mud- and sandflats, inhabits sediment surface 2-3 cm. Is a detritivore bioturbating inter-face feeder, switching between suspension and deposit feeding, depending on the tide.
Hediste diversicolor	Errant Nereid polychaete. Has well developed locomotory appendages. Are omnivores switching between suspension and selective subsurface deposit feeding. Found intertidally under brackish conditions. Burrows found in black muddy sand.
Pygospio elegans	Spionid polychaete. Sedentary tube-dwelling surface deposit feeder. Tube constructed of fine-sand grains embedded in mucus. Located from mid-shore to the sublittoral.
Streblospio shrubsolii	Spionid polychaete. Sedentary tube-dwelling deposit feeder. Tube constucted of fine-grained mud. Located in mudflats, inter- and subtidally.
Tubificoides benedii	Tubificid oligochaete. A subsurface deposit feeding detritivore. Located in estuarine sediments enriched by organic matter.

Table 1.2: Skeffling mudflat macro-faunal community of the high-shore.

Species	Sharpless (2000)	Mazik (1998)	Widdows, *et al.*, in: Black and Paterson (1998)
Carcinus maenas	p	a	a
Arenicola marina	p	a	a
Eteone longa/flava agg	p	p	p
Hediste diversicolor	p	p	p
Nepthys hombergii	p	p	a
Pygospio elegans	p	a	p
Spionidae sp. indet.	a	p	p
Streblospio shrubsolii	p	a	a
Cerastroderma edule	p	a	a
Macoma balthica	p	p	p
Scrobicularia plana	p	a	a
Retusa obtusa	p	p	a
Hydrobia ulvae	p	p	a
Tubificidae sp. indet.	p	p	p
Enchytraeidae sp. indet.	a	p	a
Nematoda	p	p	a

Note: "a" denotes absent and "p" denotes present.

2 Vertical migration of macro-fauna into simulated dredged material

2.1 Introduction

The reconstruction of benthic communities, within microcosms, were developed in other studies to allow the continuation of natural biological processes which are often a source of small-scale biological disturbance like species interactions such as bioturbation (Brey, 1991; Mermillod-Blondin, *et al.*, 2005), predator-prey relationships and sedimentary-biological interactions. Recently, sediment manipulation studies have involved the use of multi-species testing which was considered a useful tool to highlight specific responses that occur as a result of environmental-biological interactions (Mermillod-Blondin, *et al.*, 2005). Many abiotic and biotic factors influence the development of a community over time. It is often not possible to assess the effects of individual factors in isolation. Subsequently laboratory studies, for example, have been undertaken to determine the extent of these effects: Chandrasekara and Frid (1998) manipulated the silt and water content of experimental sediment treatments, Ford, *et al.*, (2001) manipulated the organic content of experimental sand treatments and Schratzberger, *et al.*, (2000a) used manipulated sediment treatments of fine-grained and sand sediments.

More detailed and precise information is required as there have been only a few aquaria microcosm experiments to consider the role of macro-zoobenthic vertical migration following burial by the disposal of simulated dredged material (Maurer, *et al.*, 1980-81, 1981, 1982, 1986; Chandrasekara and Frid, 1998; Essink, 1999; Sharpless, 2000; Miller, *et al.*, 2002). In contrast, investigations into the role of the meio-benthic component in the re-colonization of defaunated sediment has also been assessed in the field (Somerfield, *et al.*, 1995; Boyd, 1999; Schratzberger, *et al.*, 2004a) and in laboratory manipulation experiments where an overburden of simulated dredged material was placed onto nematode assemblages (Schratzberger and Warwick, 1998; Schratzberger, *et al.*, 2000a, 2000b, 2004b).

The ability of individual species to escape burial by vertical migration may be related to the mode of life. More specifically, mobile benthic infauna and some epibenthic fauna can achieve the vertical migration into an overburden of dredged material. However, survival may be dependent on burial depth, structure, duration and temperature (Maurer, *et al.*, 1980-81, 1981, 1982 & 1986; Chandrasekara and Frid, 1998). Many infaunal species exhibit an innate burrowing ability and are better adapted for upward migration through the sediment matrix of an overburden. This is necessary in order to re-occupy pre-burial positions in proximity to the sediment-water interface (Chandrasekara and Frid, 1998; Elliott, *et al.*, 2000) for feeding and ventilation purposes. Therefore, the escape ability may be related to species morphology such a species with well-developed appendages used for locomotion are more able to vertically migrate to the surface of an overburden. For example, *Hediste diversicolor* (O.F. Müller) a Nereidae polychaete has well-developed parapodia (Trevor, 1976, 1978) and can successfully burrow up through a 10 cm deposition of fine-grained sediment (Sharpless, 2000). In some cases, however, the mortality rates of macro-invertebrates may be high because not all organisms have the ability to migrate upward into a large overburden of sediment (French, 1997; Maurer, *et al.*, 1980-81, 1982), this is true of certain species of epibenthic fauna which have a limited burrowing ability and may be more sensitive to burial. Therefore, it may be necessary to use a suite of benthic macro-invertebrates as indicators of restoration/recovery, as recovery may occur at different rates and have different species distributions (Moy and Levin, 1991).

This study investigates the re-colonization ability of temperate estuarine macro-zoobenthos following burial by simulated dredged material deposition. Defaunated native fine-grained sediment and exotic sandy sediment treatments were investigated and placed at low and high frequencies. The vertical migration of macro-fauna into the sediment overburden was assessed during this study with different amounts to a total depth of 10 cm, 15 cm and 20 cm.

2.1.1 Aims, objectives and null hypotheses

The specific aims of this research were to understand the relationship between the amount of simulated dredged material deposition and the frequency of deposition and macro-faunal re-colonization through vertical migration. The main objectives of the study were to compare (a) univariate community characteristics and (b) species composition of the re-colonized simulated dredged material placed in a single low frequency deposition of 10 cm, 15 cm and 20 cm treatment depths and at the same treatment depths but placed in smaller high frequency amounts. Lastly, to suggest which species are able to withstand burial and are able to vertically migrate to a natural position within the sediment. In particular, the following null hypotheses were tested: (1) the distribution of macro-fauna within the vertical profile of the control or the experimental sediment treatments does not increase in mean abundance towards the sediment surface and (2) the vertical migration of macro-fauna into depositions of simulated dredged material placed in different amounts and frequencies to a depth of between 10 cm and 20 cm is not different to the position of macro-fauna in the mudflat control. As part of the non-site specific component of the project a laboratory-based sediment manipulation experiment was conducted during the winter months of 2000/2001.

2.2 Methods and Materials

A manipulative aquarium experiment was undertaken to investigate macro-faunal response to a sediment overburden using two sediment types of simulated dredged material. A series of Perspex corers (6.4 cm id) of varying heights (ht) (between 30 & 50 cm ht) were used to contain each mudflat core sample. A total of 52 mudflat cores 20 cm depth (d) x 6.4 cm id were extracted from the Skeffling mudflats, on the outer part of the Humber Estuary, Eastern England during February 2001. To assess the nature of the benthic community a further five cores were removed from an undisturbed area within the sampling site. Each sediment corer was stored upright, with the mudflat core retained inside and transported back to the laboratory aquarium. A space remained above the mudflat core within each sediment corer for later simulated dredged material deposition. Parafilm was used to seal the lower end of each corer and a 250 µm aperture mesh was secured over the top end, thus preventing any animals (macro-fauna specifically) from escaping. In the aquarium the sediment microcosms were placed into a random block design and submerged in an upright position within a 50 litre (l) tank and left to acclimatize for 24 hours (h). The tank had been set-up and in operation i.e. water had been circulated and aerated at a winter temperature of 9 °C, at a salinity of 29, with a 12:12 h light: dark regime, for one week and was regarded as similar to environmental conditions experienced at the field site, during the spring/autumn period. No additional food was added to the microcosms as this could have influenced the distribution of macro-fauna within the mud-core vertical profile but the microphytobenthos was maintained through the light regime. Physical and chemical parameters within the tank such as salinity, temperature, dissolved oxygen and pH, were kept constant throughout the experiment.

Each microcosm was secured and left to acclimatize in the aquarium tank for 48 hours. To simulate the dredged material sediment types and amount required for the experiment, a total of 11.5 litres (l) of fine-grained sediment was collected from approximately the top 10 cm surface layers of the high-shore area at the Skeffling mudflats and a total of 11.5 l of sandy sediment was collected from a nearby beach. The fine-grained sediment collected from the field site was defaunated (of macro-fauna) by passing the material through a sieve (Maurer, *et al.* 1980-81, 1981, 1982) with a 500 µm aperture mesh screen and left to settle for 48 h. Any invertebrates were removed by sorting through the material under a dissecting microscope (thus also reducing the level of organic material present in the sediment). The defaunated fine-grained sediment was used to produce the sediment slurry known as the mud treatment material. The mud treatment was homogenized by mixing 8.6 l fine-grained sediment simulated dredged material and 2.8 l of filtered seawater. The sand treatment material was defaunated by passing through sieves of a 1 mm and a 500 µm aperture mesh screen, thus separating the coarser grained sand material from the fine and aiding macro-faunal extraction. All macro-fauna were extracted from the sand treatment by sorting through the material using a white tray and magnifying lamp. The two sediment treatments were homogenized separately to produce two types of simulated dredged material: fine-grained mud and sand.

The sediment was later defaunated using a freeze-thaw method and frozen at a temperature of $-20\ ^{0}C$ to remove any contamination of all life stages of the macro- and meio-faunal organisms. The experimental sediment treatments were homogenized a second time before treatment deposition on to the mudflat cores occurred. The survival following burial and the ability of macro-fauna to migrate vertically into simulated sandy and fine-grained dredged material overburden was investigated.

Twelve treatments were used, including sand (S) and native mud (M). The mudflat cores without treatments were used as a control (C) and all treatments and the control had four replicates. Each sediment treatment was placed onto the central area of the mudflat core surface within the sediment microcosm. A single low frequency deposition of 10 cm (1), 15 cm (2) and 20 cm (3) of each treatment: M1 (1, 2 & 3) and S1 (1, 2 & 3) were placed on day 1 (Table 2.1) (Figure 2.1). To examine the effect of both amount and frequency, six smaller high frequency depositions (M6 or S6) of 54 ml (1), 81 ml (2) and 107 ml (3) of each treatment: M6 (1, 2 & 3) and S6 (1, 2 & 3) were placed (Table 2.1) (Figure 2.1) on the following days: 1, 4, 8, 12, 16 and 20. The total amount of high frequency deposition mud (M6) and sand (S6) treatments were equal to a single low deposition of mud (M1) or sand (S1) treatments (Table 2.1). The experiment ran for approximately 2.5 months. Migration into the overburden was assessed by extracting the macro-fauna after the vertical profiling of the deposited material as follows: the top 5 cm of each microcosm was sectioned into 1 cm increments and thereafter 3 cm increments were used to give the mean horizontal sections. Macro-faunal extraction occurred after each horizontal section sample had been immediately sieved through a 500 µm aperture mesh screen. Species survival/mortality rate as a consequence of burial was considered during this study and faunal extraction of the upper horizontal sections (0-1 and 1-2 cm depths) occurred immediately and any organisms extracted were checked for mortality by detection of movement within the Petri dish. Any organisms present within the remaining horizontal sections were quickly checked for mortality before fixing in buffered 4% formo-saline solution with Rose Bengal stain to aid extraction of the fauna (Williams & Williams, 1974). All fixed sections were left for at least 48 h, to allow staining to take place prior to faunal extraction and rinsed with water over a 212 µm aperture mesh screen. All specimens were then identified, enumerated and preserved in 70 % Industrial Methylated Spirits (IMS).

Table 2.1: Volume of treatment deposition: M1, M6, S1 & S6 ($n = 4$).

Simulation Depth (cm)	Low-frequency treatments: M1 + S1 Volume (ml)	High-frequency treatments: M6 +S6 Volume (ml)
0	0	0
10	322	54
15	483	81
20	643	107

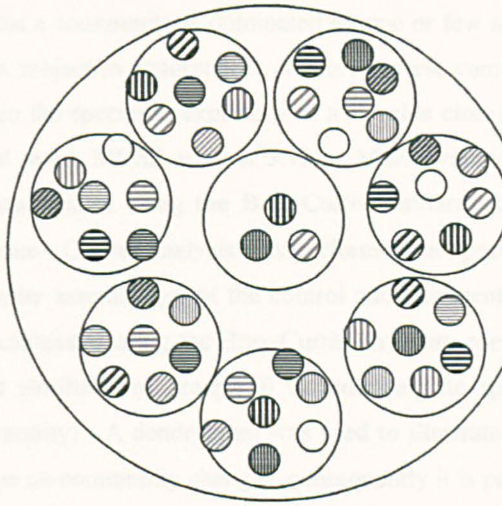


Figure 2.1: Experimental set-up of low and high frequency deposition treatments and the control ($n = 4$).

Treatment key

Mud 1.1	Sand 1.1
Mud 1.2	Sand 1.2
Mud 1.3	Sand 1.3
Mud 6.1	Sand 6.1
Mud 6.2	Sand 6.2
Mud 6.3	Sand 6.3
Control	

2.2.1 Data analyses

The mean (± S.E.) abundances of each species in the control and experimental sediment treatments (0-11 cm depth) were determined. The vertical profile of mean abundance per taxa for low/high frequency treatment depositions and the control was determined with (±) pooled Poisson confidence intervals (C.I.) (used to avoid an overestimate of C.I. as some species mean abundances were low). Normality was tested using the Kolmogorov-Smirnov test and then a square root plus zero abundance correction factor (0.5) transformation was applied to the data to correct for non-normality. The Levene's test was used to test for homogeneity of variances and then depending on assumptions being met a 1-way ANOVA with linear contrasts was applied to test for linear trends of macro-faunal mean abundances within the vertical profile of the sediment treatments. Secondly, a two-way ANOVA was applied to the low and high deposition sediment treatments to test the null hypothesis that the two factors: treatment and depth, do not significantly ($p<0.05$) affect the vertical migration of macro-fauna. Tukey multiple comparisons tests were used to determine significant differences ($p<0.05$) between treatment type and depth. All univariate analyses were conducted using SPSS version 13. The Shannon-Wiener index (H') was used to indicate community diversity. This integrates species richness and relative abundance (Barker, *et al.*, 1987) and high values indicate high diversity, whilst low values indicate low diversity. Pielou's evenness index (J') was used to give a measure of the relative abundance of each species. A low diversity is expressed as a low J' value and indicates that a community is dominated by one or few species, a situation which often occurs in low diversity areas subject to disturbance. A more diverse community where there is an even spread of individuals between the species is expressed as a J' value closer to 1. Both univariate indices (H' and J') were performed using MVSP version 3.12a. Multivariate classification analysis (cluster analysis) of the data was undertaken using the Bray-Curtis similarity coefficient and group average (UPGMA) clustering technique. Cluster analysis was performed on species composition to assess (dis) similarities between community assemblages of the control and treatments. The similarity between the control and treatments was calculated using the Bray-Curtis similarity coefficient to produce a similarity matrix showing the percent similarity of groups (0 % indicating no species in common and 100 % indicating an identical community). A dendrogram was used to illustrate the relative importance of the control and the treatment type on community changes, consequently it is possible to define groups of sites with similar species composition at a predefined level of similarity. All multivariate analyses were performed using MVSP version 3.12a.

2.3 Results

2.3.1 Univariate analysis

A total of 12 taxa were sampled from all the treatments and the control. The four numerically dominant taxa comprised of 93.0 % of the total individuals. The four taxa included the bivalves *Abra tenuis* (Montagu) (0.8 %) and *Macoma balthica* (Linnaeus) (6.6 %), the Spionid polychaete *Pygospio elegans* (Claparède) (11.0 %) and the oligochaete *Tubificoides benedii* (Udekem) (74.7 %). *Tubificoides benedii* had the highest mean abundance throughout the control (60.0 ± 13.5) and treatments (28.3 ± 15.2 to 80.3 ± 18.0) (Table 2.2). In contrast, nematodes had the lowest mean abundance throughout the control (6.5 ± 3.7) and treatments (0.3 ± 0.3 to 4.0 ± 2.5).

The total mean abundance of macro-fauna was highest in the control (98.3) followed by the mean abundance of the mud treatments (79.2) then the sand treatments (78.7) (Figure 2.2 a). The mean abundance of macro-fauna in the single deposition treatments of mud (87.7) was slightly higher than the single depositions of sand (82.8) and the mean abundance of macro-fauna in the multiple depositions of mud (70.8) was less than the multiple depositions of sand (74.7). The single deposition treatment of sand (S1.1) had the highest total mean abundance (106.3) overall and the multiple deposition treatment of mud (M6.2) had the lowest (47). The mean species richness in the mud treatments (9 to 13) were, equal to or higher than the control (9) and the mean number of species in the sand treatments were equal to the control or less (9 to 6) (Figure 2.2 b). The mud treatment deposited in a single amount of 10 cm (M1.1) had the greatest mean number of species (13) overall, followed by the mud treatment deposited in thin veneers to a total depth of 10 cm (M6.1) and had a mean number of 12 species. Only two sand treatments had an equal or greater mean number of species when compared to the control, both were deposited as thin veneers to a total depth of 10 cm and 15 cm and had a mean number of 9 and 10 species respectively. Overall the mud treatments had a higher mean number of species of 10.5 when compared to the control (9) or the sand treatments (7.9). The highest diversity and species evenness occurred in the control and the multiple depositions sand treatment communities (S6.3) (Figures 2.2 c-d). The sand treatments communities were more diverse and had a greater evenness when compared to the mud treatment communities. The multiple deposition mud treatment communities were more diverse and had a greater evenness than the single deposition mud communities.

Table 2.2: Mean (± SE; n = 4) abundances of species in the control and experimental sediment treatments (0-11 cm depth).

	Treatment (low deposition)							Treatment (high deposition)					
Species	Control	Mud 1.1	Mud 1.2	Mud 1.3	Sand 1.1	Sand 1.2	Sand 1.3	Mud 6.1	Mud 6.2	Mud 6.3	Sand 6.1	Sand 6.2	Sand 6.3
Abra tenuis	2.8 ± 0.6	0.3 ± 0.3	0.5 ± 0.3	0.8 ± 0.5	0.0	0.0	0.8 ± 0.3	1.3 ± 0.8	1.5 ± 0.9	0.5 ± 0.5	0.0	0.3 ± 0.3	1.5 ± 0.6
Macoma balthica	6.8 ± 2.4	11.8 ± 4.5	9.3 ± 2.3	7.5 ± 4.1	4.3 ± 1.8	3.5 ± 1.3	5.0 ± 0.8	6.0 ± 3.1	2.8 ± 1.6	7.3 ± 3.7	5.5 ± 1.0	5.0 ± 2.7	6.5 ± 4.4
Pygospio elegans	25.3 ± 10.4	2.8 ± 2.1	0.8 ± 0.8	0.8 ± 0.8	29.3 ± 12.4	10.0 ± 5.3	20.3 ± 8.6	2.5 ± 1.3	1.8 ± 1.4	3.3 ± 3.3	1.5 ± 1.5	17.8 ± 8.3	16.3 ± 6.0
Tubificoides benedii	60.0 ± 13.5	72.8 ± 17.5	73.5 ± 16.7	71.8 ± 18.8	66.8 ± 4.9	28.3 ± 15.2	52.0 ± 12.3	53.3 ± 6.2	37.0 ± 13.6	80.3 ± 18.0	45.3 ± 22.3	64.3 ± 15.9	39.0 ± 14.8
Nematoda	6.5 ± 3.7	1.3 ± 0.8	1.0 ± 1.0	0.8 ± 0.8	4.0 ± 2.5	0.3 ± 0.3	0.5 ± 0.5	1.5 ± 1.5	1.0 ± 0.4	0.5 ± 0.5	3.3 ± 2.0	1.5 ± 1.2	0.5 ± 0.5

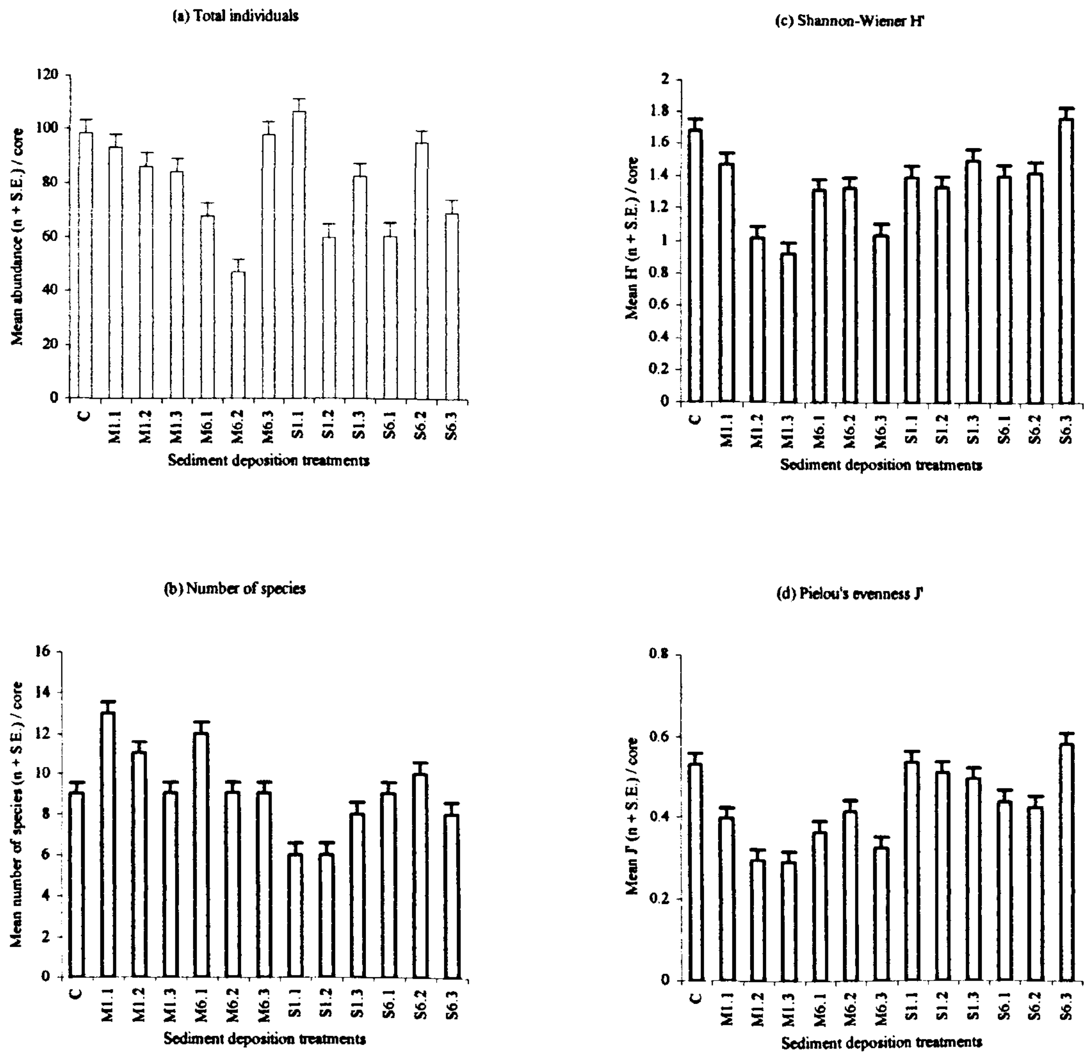


Figure 2.2 (a-d): Macro-faunal community characteristics of the experimental sediment treatments.

The vertical distribution of numerically dominant taxa within each single deposited sediment treatment (Figures 2.3 i-vi) show the two bivalve species present *A. tenuis* and *M. balthica* were restricted to the surface layers (0-3 cm) of the mudflat control and *P. elegans* was mostly positioned in the surface layers to a depth of 5 cm. However, *T. benedii* was widespread within the vertical profile of the mudflat control (0-11 cm). The most common taxa were positioned in the surface layer 1-2 cm within the vertical profile of the mudflat control and few individuals were sampled below a depth of 11 cm. The mean abundances of *A. tenuis* in the surface layers of the single deposition treatments were less than the control (Figure 2.3 i). The mean abundances of *M. balthica* were greater than the control in the surface layer (0-1 cm) of all single deposition treatments except the single 20 cm deposition of mud treatment (M1.3), which had the greatest mean abundance of the deeper layers of 5-11 cm (Figure 2.3 ii). Similarly, the mean abundances of Tellinacea juveniles were higher in the surface layers (0-3 cm) of all single deposition treatments when compared to the control (Figure 2.3 iii). The distribution of *P. elegans* was widespread within the single deposition treatments of sand and restricted to the surface layers of the mud treatments (Figure 2.3 iv). The mean abundance was greatest overall in surface layer (0-1 cm) of the sand treatment deposited in a single amount of 10 cm. *Tubificoides benedii* re-colonized the sediment treatments placed as a single amount and mean abundances were higher in most sediment treatments than the control in the surface layer (0-1 cm) (Figure 2.3 v). *Tubificoides benedii* re-colonization of the mud treatments was widespread and mean abundances exceeded the control from layers 3-11 cm. The mean abundance of nematodes was greatest in the control when compared to the sediment treatments and the re-colonization of the treatments was widespread (Figure 2.3 vi).

The vertical distribution of numerically dominant taxa within each high frequency deposition sediment treatment (Figures 2.4 i-v) show *A. tenuis* had re-colonized the surface layers (0-2 cm) and *M. balthica* was distributed throughout the upper layers (0-8 cm) of some treatments, for example, the mud treatments of 10 cm (M6.1) and 20 cm (M6.3). The high deposition of sand treatment to a depth of 10 cm (S6.1) had the greatest mean abundance of *M. balthica* in the surface layer (0-1 cm) and was highest overall (Figure 2.4 ii). *Pygospio elegans* re-colonized the surface layers (0-3 cm) of all the high frequency deposition treatments but did not exceed the mean abundance of the control (Figure 2.4 iii). However, *P. elegans* was widely distributed throughout the high deposition sand treatments of 15 cm (S6.2) and 20 cm (S6.3). *Tubificoides benedii* was widely distributed throughout the vertical profiles of the treatments and the control (Figure 2.4 iv). The mean abundances were greatest in surface layer (0-1 cm) of all sand treatments (S6.1 to S6.3) and the mud treatment of 20 cm (M6.3) when compared to the control. The distribution of nematodes was restricted to layers 1-3 cm within the control vertical profile and was higher than the sediment treatments but the vertical distribution within the sediment treatments was widespread (Figure 2.4 v).

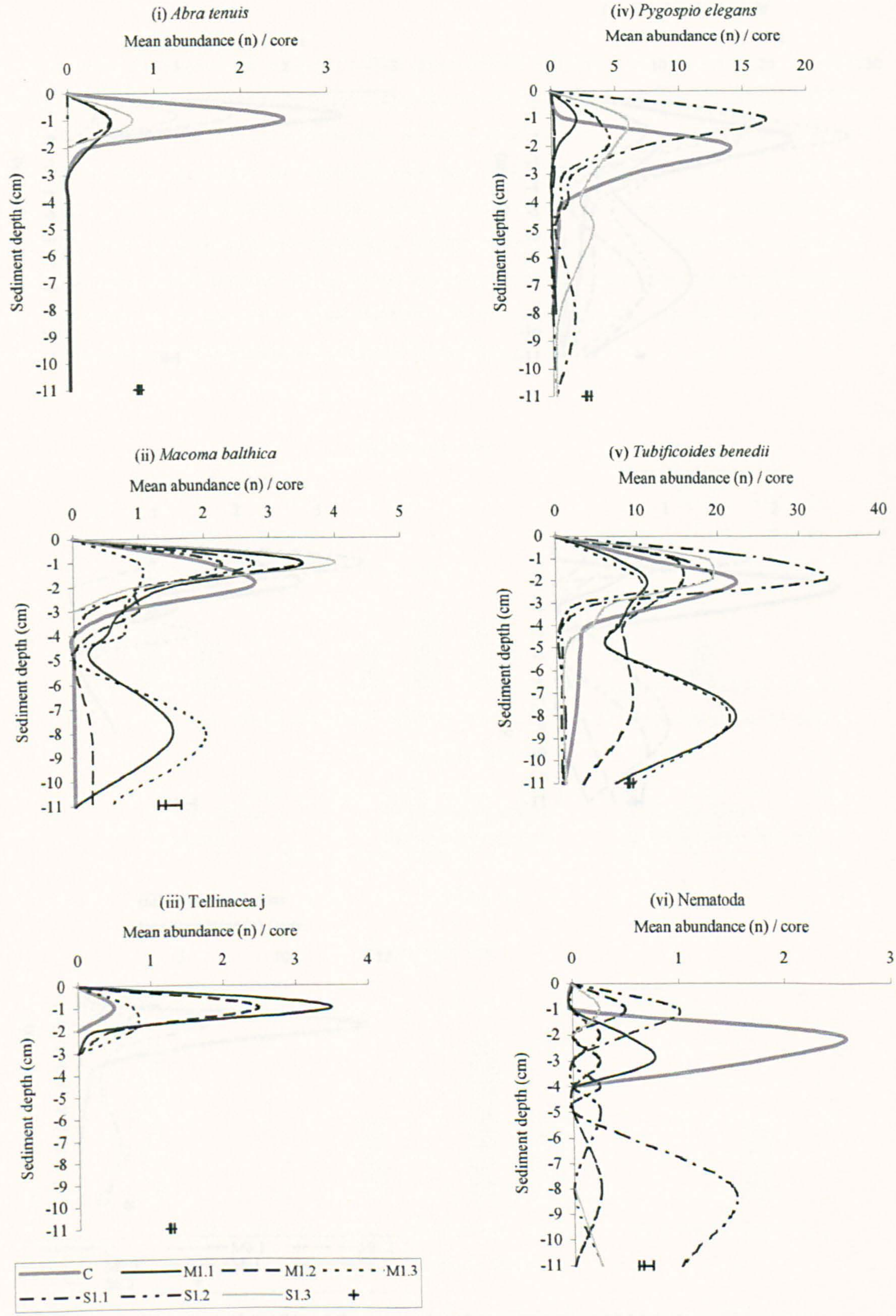


Figure 2.3 (i-vi): The vertical profile of the mean abundance per taxa for single deposition treatments and the control (n = 4). Error bars at the bottom of each figure denote (±) pooled Poisson confidence intervals.

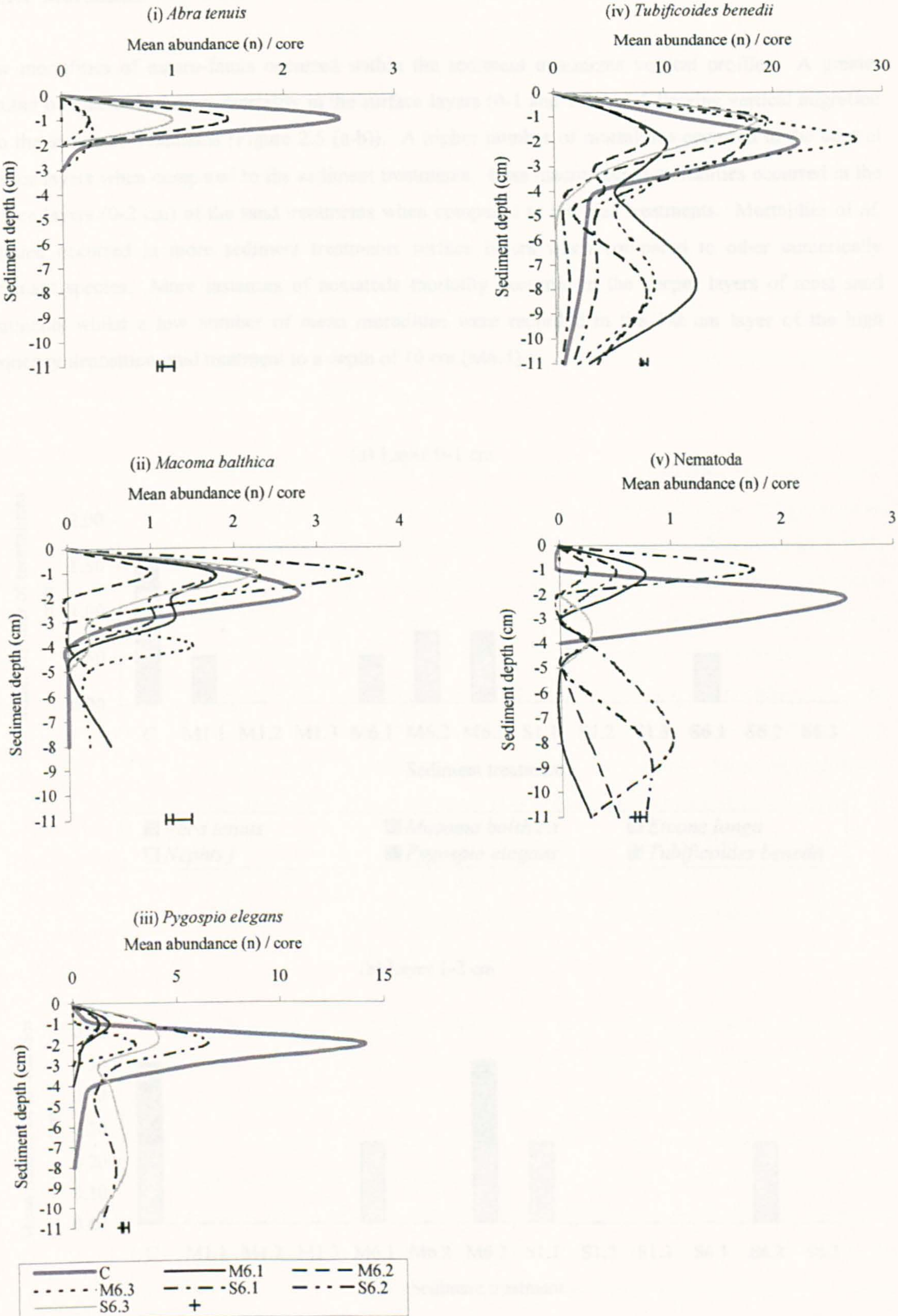
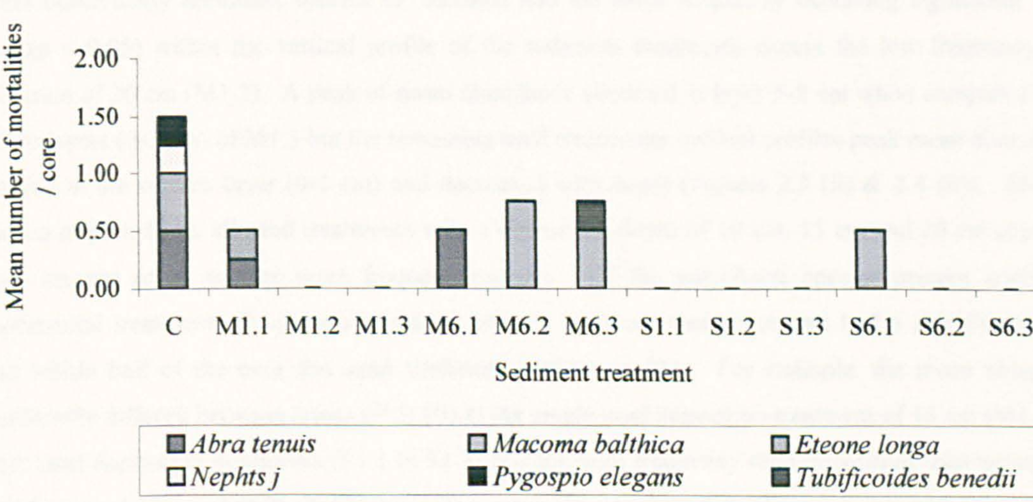


Figure 2.4 (i-v): The vertical profile of the mean abundances per taxa for high deposition treatments and the control (n = 4). Error bars at the bottom of each figure denote (±) pooled Poisson confidence intervals.

2.3.1.1 Mortalities

Few mortalities of macro-fauna occurred within the sediment treatments vertical profiles. A greater number of species had more mortality in the surface layers (0-1 and 1-2 cm) following vertical migration into the sediment treatments (Figure 2.5 (a-b)). A higher number of mortalities occurred in the control surface layers when compared to the sediment treatments. Less macro-faunal mortalities occurred in the surface layers (0-2 cm) of the sand treatments when compared to the mud treatments. Mortalities of *M. balthica* occurred in more sediment treatments surface layers when compared to other numerically dominant species. More instances of nematode mortality occurred in the deeper layers of most sand treatments whilst a low number of mean mortalities were recorded in the 1-2 cm layer of the high frequency deposition mud treatment to a depth of 10 cm (M6.1).

(a) Layer 0-1 cm



(b) Layer 1-2 cm

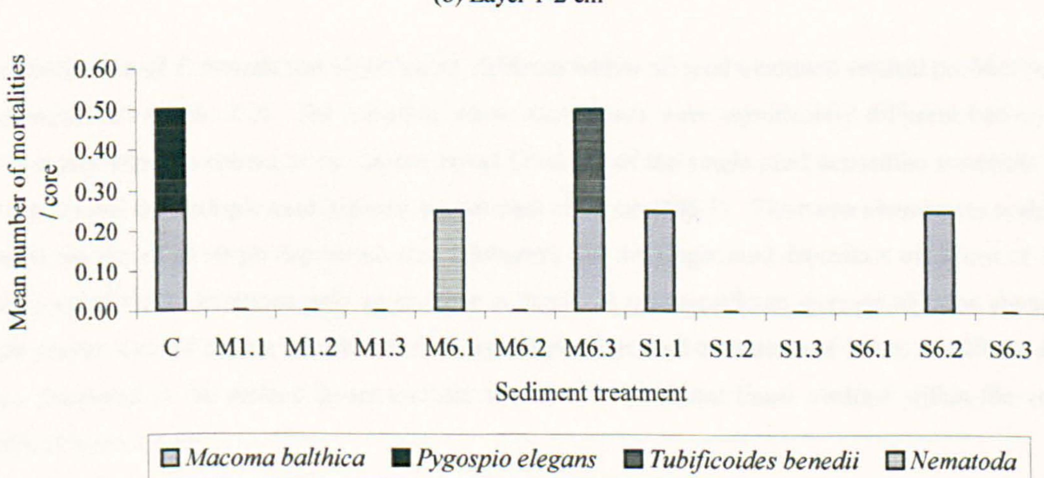


Figure 2.5 (a-b): Mean number of mortalities (n = 4) in the surface layers of the sediment treatments.

Following the significant results of a one-way ANOVA (experimental effects), further linear contrasts within ANOVA revealed linear trends within the vertical profile of the control and the experimental sediment treatments (Table 2.3). The mean abundances of *A. tenuis, M. balthica, P. elegans* and *T. benediii* in the control vertical profile significantly differed between layers ($P<0.05$) suggesting a linear trend of increased macro-faunal mean abundance towards the surface of the control vertical profile. The vertical distribution of *A. tenuis* had a significant linear trend ($P<0.05$) within the vertical profile of the single mud deposition treatments of 15 cm (M1.2) and 20 cm (M1.3) and the high frequency deposition treatment of mud (M6.2). Fewer individuals vertically migrated from the base mudflat cores into the sand treatments when compared to the mud treatments, the number of individuals may have been low or absent from the mudflat cores (Figures 2.3 (i) & 2.4 (i)). However, the mean abundances of *A. tenuis* was significantly different between the layers of the single sand deposition treatment of 20 cm (S1.3) and the high frequency sand deposition treatment of 20 cm (S6.3).

Of the numerically dominant species *M. balthica* had the most frequently occurring significant linear trend ($p < 0.05$) within the vertical profile of the sediment treatments except the low frequency mud deposition of 20 cm (M1.3). A peak of mean abundance occurred in layer 5-8 cm when compared to the surface layers (0-3 cm) of M1.3 but the remaining mud treatments vertical profiles peak mean abundances occurred in the surface layer (0-1 cm) and decreased with depth (Figures 2.3 (ii) & 2.4 (ii)). *Macoma balthica* migrated into all sand treatments with a deposition depth of 10 cm, 15 cm and 20 cm placed as single amount or as smaller more frequent amounts. Of the polychaete species present within the experimental treatments *P. elegans* migrated into all sediment treatments and had a significant linear trend within half of the mud and sand treatment vertical profiles. For example, the mean abundance significantly differed between layers ($P<0.05$) in the single mud deposition treatment of 10 cm (M1.1), all single sand deposition treatments (S1.1 to S1.3) and the high frequency mud deposition treatments of 10 cm (M6.1) and 15 cm (M6.2) (Table 2.3). The mean abundances of *P. elegans* per significant sediment treatment were greatest in the surface layers (0-2 cm) and decreased with depth (Figures 2.3 (iv) & 2.4 (iii)).

The distribution of *T. benedii* was significantly different within all sand treatment vertical profiles but few mud treatments (Table 2.3). For example, mean abundances were significantly different between the upper layers when compared to the deeper layers ($P<0.05$) of the single mud deposition treatment of 15 cm (M1.2) and the multiple mud deposition treatment of 20 cm (M6.3). The mean abundances within the vertical profiles of all single deposition sand treatments and the single mud deposition treatment of 15 cm (M1.2) significantly decreased with an increase in depth. A non-significant increase of mean abundance in the deeper layer of 5-8 cm occurred in the single deposition mud treatments of 10 cm and 20 cm depths when compared to the surface layers and did not have a significant linear contrast within the vertical profile (Figure 2.3 v).

Similarly, the vertical distribution of *T. benedii* in the multiple deposition sand treatments and the multiple deposition of mud to a depth of 20 cm (M6.3) had significant peaked mean abundances in the surface layers when compared to the deeper layers. In contrast, the multiple deposition of mud treatments to a depth of 10 cm and 15 cm (M6.1 & M6.2) had non-significant peaked mean abundances in the deeper layer of 5-8 cm and did not have a significant linear contrast within the vertical profile (Figure 2.4 iv). Nematoda mean abundance was not significantly different between layers (P>0.05) in any of the treatment vertical profiles. The H_{01} was rejected for all significant one-way ANOVA values and the mean abundances of certain macro-faunal species did have a significant linear relationship and decreased with depth within the vertical profile of some sediment treatment cores. In general the distribution of macro-faunal species in the surface layers appeared different to the lower layers of all significant (P<0.05) sediment treatments and the control (Figure 2.3 i-vi) (Figure 2.4 i-v).

Table 2.3: One-way ANOVA with linear contrasts of square root + zero correction factor transformed abundance data of four common taxa (0-11 cm depth) (n = 4).

Taxon	*Abra tenuis*			*Macoma balthica*			*Pygospio elegans*			*Tubificoides benedii*		
Source	DF	F	*p*	DF	F	*p*	DF	F	*p*	DF	F	*p*
Control	1	62.23	**<0.001**	1	23.81	**<0.001**	1	18.67	**<0.001**	1	39.36	**<0.001**
M1.1	1	3.24	0.086	1	20.45	**<0.001**	1	4.36	**0.049**	1	0.90	0.354
M1.2	1	6.75	**0.017**	1	31.18	**<0.001**	1	3.00	0.098	1	7.41	**0.013**
M1.3	1	5.97	**0.023**	1	0.44	0.515	1	0.75	0.396	1	1.92	0.181
M6.1	1	2.25	0.148	1	13.19	**0.002**	1	12.67	**0.002**	1	0.44	0.516
M6.2	1	9.77	**0.005**	1	5.64	**0.027**	1	5.59	**0.028**	1	0.96	0.337
M6.3	1	3.13	0.092	1	8.07	**0.010**	1	1.57	0.224	1	22.53	**<0.001**
S1.1	-	-	-	1	15.76	**0.010**	1	16.42	**<0.001**	1	302.27	**<0.001**
S1.2	-	-	-	1	11.35	**0.003**	1	8.38	**0.009**	1	12.60	**0.002**
S1.3	1	20.25	**<0.001**	1	74.81	**<0.001**	1	7.21	**0.014**	1	31.04	**<0.001**
S6.1	-	-	-	1	34.64	**<0.001**	1	3.00	0.098	1	12.45	**0.002**
S6.2	1	2.25	0.148	1	12.08	**0.002**	1	1.72	0.204	1	9.75	**0.005**
S6.3	1	15.84	**<0.001**	1	10.38	**0.004**	1	1.52	0.232	1	32.48	**<0.001**

Bold values indicate a significant linear relationship between a taxon distribution within the vertical profile of the control or the experimental sediment treatments, $p < 0.05$. ("-" Denotes zero abundance).

2.3.1.2 Single deposition treatments

The single deposition treatment vertical profiles of the two bivalve species differed. In general the mean abundances of *M. balthica* were higher than *A. tenuis* and numbers of *A. tenuis* were low overall. The vertical distribution of *A. tenuis* in the single deposition treatment types of mud and sand were significantly lower to the control in layer 0-1 cm (Table 2.4). Individuals did vertically migrate into the surface layers of the single deposition treatments but migration was affected by treatment type. The single depositions of mud treatments were significantly different to the control when comparing the mean abundances of *M. balthica* in the 3-4 cm profile (Table 2.4).

Macoma balthica did re-colonize the single frequency deposition of mud treatments of the 10 cm (M1.1) and 15 cm (M1.2) and had greater mean abundances in the surface layer (0-1 cm) when compared to the control. Mean abundances subsequently decreased with depth (from layer 0-1 cm to 2-3 cm). However, mean abundances in layer 3-4 cm of the mud treatments were significantly greater than the control. Therefore, the vertical distribution was affected by treatment type when a single low frequency amount of mud treatment was added and although individuals did colonize the surface layers of all mud treatments, the distribution was more widespread within the vertical profiles when compared to the mudflat control. The vertical distributions in the single depositions of sand treatments were not significantly different to the control and vertical migration was not affected by the sand treatment depositions.

The vertical distributions of *P. elegans* in the single deposition treatment types of mud and sand were significantly different to the control in layers 1-2 cm and 2-3 cm (Table 2.4). Similarly, the mean abundances in the single deposition treatments of mud were significantly different to the control in layers 3-4 cm. Therefore, the vertical migration was significantly affected by the sediment treatment types placed in a single amount and the mean abundances were significantly less in the mud treatments between layers 1-2 cm and 3-4 cm and significantly less in the sand treatment types between layers 1-2 cm and 2-3 cm when compared to the control vertical profile. Overall the vertical distribution was more widespread and in higher abundances in the sandy treatment types of low depositions when compared to the mud treatments.

The vertical distributions of *T. benedii* present in the single deposition mud treatment types were significantly different to the control in layers 1-2 cm and 4-5 cm (Table 2.4). Similarly, the mean abundances in the single deposition treatments of sand were significantly different to the control in layers 4-5 cm. The mean abundances in layer 1-2 cm of the mud treatments were significantly less than the control. However, in layer 4-5 cm the mean abundances in the mud treatments were significantly higher than the control and the mean abundances in layer 4-5 cm of the low frequency sand treatment types were significantly less than the control. The vertical distribution was widespread within all low frequency deposition treatment types and in general the vertical distribution in the sand treatment types had a similar trend to the control with a peak of mean abundance in layer 1-2 cm and the distribution in the mud treatment types were bimodal, peaking in layer 1-2 cm and 5-8 cm.

Table 2.4: Two-way ANOVA of square root + zero correction factor transformed invertebrate data of the surface layers (0-5 cm) of the low deposition treatments (n = 4).

Taxa	Treatment layer (cm)	Source	Df	F	*P*	Sig. from control*
A. tenuis	0-1	**Treatment**	2	11.86	**<0.001**	1, 2
		Depth	2	0.17	0.842	
		Treatment*Depth	4	2.21	0.095	
	1-2	Treatment	2	1.75	0.193	
		Depth	2	0.25	0.781	
		Treatment*Depth	4	0.25	0.907	
	2-3	Treatment	2	-	-	
		Depth	2	-	-	
		Treatment*Depth	4	-	-	
	3-4	Treatment	2	-	-	
		Depth	2	-	-	
		Treatment*Depth	4	-	-	
	4-5	Treatment	2	-	-	
		Depth	2	-	-	
		Treatment*Depth	4	-	-	
M.balthica	0-1	Treatment	2	0.48	0.623	
		Depth	2	0.02	0.985	
		Treatment*Depth	4	0.28	0.891	
	1-2	Treatment	2	1.78	0.188	
		Depth	2	0.00	0.997	
		Treatment*Depth	4	0.05	0.995	
	2-3	**Treatment**	2	3.936	**0.032**	-
		Depth	2	0.101	0.904	
		Treatment*Depth	4	0.068	0.991	
	3-4	**Treatment**	2	6.671	**0.004**	1
		Depth	2	0.638	0.536	
		Treatment*Depth	4	0.638	0.640	
	4-5	Treatment	2	1.000	0.381	
		Depth	2	1.000	0.381	
		Treatment*Depth	4	1.000	0.425	
P. elegans	0-1	Treatment	2	0.81	0.453	
		Depth	2	0.03	0.969	
		Treatment*Depth	4	0.73	0.578	
	1-2	**Treatment**	2	17.863	**<0.001**	1, 2
		Depth	2	0.052	0.950	
		Treatment*Depth	4	0.490	0.743	
	2-3	**Treatment**	2	13.883	**<0.001**	1, 2
		Depth	2	0.261	0.772	
		Treatment*Depth	4	0.261	0.900	
	3-4	**Treatment**	2	4.556	**0.020**	1
		Depth	2	0.356	0.704	
		Treatment*Depth	4	0.356	0.837	
	4-5	Treatment	2	2.400	0.110	
		Depth	2	1.718	0.198	
		Treatment*Depth	4	1.718	0.175	

Bold value indicates significant at 0.05. * Refers to treatments that were found to be significantly different from the control (Tukey's multiple comparison test, $p < 0.05$) '1' indicates mud treatments and '2' indicates sand treatments. ("-" In F & *P* columns denotes zero abundance).

Table 2.4 continued: Two-way ANOVA of square root + zero correction factor transformed invertebrate data of the surface layers (0-5 cm) of the low deposition treatments ($n = 4$).

Taxa	Treatment layer (cm)	Source	Df	F	*P*	Sig. from control*
T. benedii	0-1	Treatment	2	0.45	0.645	
		Depth	2	0.13	0.879	
		Treatment*Depth	4	0.17	0.952	
	1-2	**Treatment**	2	4.064	**0.029**	1
		Depth	2	0.506	0.609	
		Treatment*Depth	4	0.965	0.442	
	2-3	**Treatment**	2	8.930	**<0.001**	-
		Depth	2	0.075	0.928	
		Treatment*Depth	4	0.552	0.699	
	3-4	**Treatment**	2	4.191	**0.026**	-
		Depth	2	0.296	0.746	
		Treatment*Depth	4	0.515	0.725	
	4-5	**Treatment**	2	15.105	**<0.001**	1, 2
		Depth	2	0.395	0.678	
		Treatment*Depth	4	0.284	0.885	

Bold value indicates significant at 0.05. * Refers to treatments that were found to be significantly different from the control (Tukey's multiple comparison test, $p < 0.05$) '1' indicates mud treatments and '2' indicates sand treatments. ("-" In F & *P* columns denotes zero abundance).

2.3.1.3 High deposition treatments

The smaller more frequent sediment deposition treatment vertical profiles of the two bivalve species present differed. In general the mean abundances of *M. balthica* were higher than *A. tenuis*. The vertical distribution of *A. tenuis* in the high deposition treatment types of mud and sand were significantly different to the control in layer 0-1 cm (Table 2.5). The mean abundances were significantly lower in the surface layer (0-1 cm) of the high deposition treatment types when compared to the control. *Abra tenuis* individuals did vertically migrate into the surface layers of the high frequency deposition treatment types but migration was affected by treatment type. The frequent smaller depositions of sediment treatments were not significantly different to the control when comparing the mean abundances of *M. balthica* in the vertical profiles (Table 2.5) however individuals did re-colonization the sediment treatments and the surface layers had the greatest mean abundances throughout the vertical profiles and was especially high in the high frequency deposition of sand to a depth of 10 cm (S6.1). Therefore the ability of *M. balthica* to vertically migrate was not affected by the type of sediment deposition when smaller high frequency depositions of mud or sand were added.

The vertical distribution of *P. elegans* in the high frequency deposition treatment types of mud and sand were significantly different to the control in layers 1-2 cm and 2-3 cm (Table 2.5). Similarly, the mean abundances in the high frequency deposition treatments of mud were significantly different to the control in layers 3-4 cm. Therefore, the vertical migration of *P. elegans* was significantly affected by the sediment treatment types placed in smaller high frequency amounts and the mean abundances were significantly less in the mud treatments between layers 1-2 cm to 3-4 cm and significantly less in the sand treatment types between layers 1-2 cm to 2-3 cm when compared to the control vertical profile. Overall the vertical distribution of *P. elegans* was more widespread in the sandy treatment types of high depositions when compared to the mud treatments.

The vertical distributions of *T. benedii* in the high frequency depositions of mud treatments were significantly different to the control in layers 2-3 cm (Table 2.5). However, the vertical distributions in the high frequency depositions of sand treatments were not significantly different to the control. The mean abundances in layer 2-3 cm of the mud treatments were significantly less than the control. The vertical distribution was widespread within all treatment types and bimodal peaks were observed in the mud treatments. The mean abundance in layer 1-2 cm of the mud treatment placed to a depth of 20 cm (M6.3) had the highest mean abundance overall.

Table 2.5: Two-way ANOVA of square root + zero correction factor transformed invertebrate data of the surface layers (0-5 cm) of the high deposition treatments ($n = 4$).

Taxa	Treatment layer (cm)	Source	Df	F	*P*	Sig. from control*
A. tenuis	0-1	**Treatment**	2	11.86	**<0.001**	1, 2
		Depth	2	0.17	0.842	
		Treatment*Depth	4	2.21	0.095	
	1-2	Treatment	2	1.75	0.193	
		Depth	2	0.25	0.781	
		Treatment*Depth	4	0.25	0.907	
	2-3	Treatment	2	-	-	
		Depth	2	-	-	
		Treatment*Depth	4	-	-	
	3-4	Treatment	2	-	-	
		Depth	2	-	-	
		Treatment*Depth	4	-	-	
	4-5	Treatment	2	-	-	
		Depth	2	-	-	
		Treatment*Depth	4	-	-	

Bold value indicates significant at 0.05. * Refers to treatments that were found to be significantly different from the control (Tukey's multiple comparison test, $p < 0.05$) '1' indicates mud treatments and '2' indicates sand treatments. ("-" In F & *P* columns denotes zero abundance).

Table 2.5 continued: Two-way ANOVA of square root + zero correction transformed invertebrate data of the surface layers (0-5 cm) of the high deposition treatments ($n = 4$).

Taxa	Treatment layer (cm)	Source	Df	F	*P*	Sig. from control*
M.balthica	0-1	Treatment	2	0.48	0.623	
		Depth	2	0.02	0.985	
		Treatment*Depth	4	0.28	0.891	
	1-2	Treatment	2	2.20	0.130	
		Depth	2	0.56	0.577	
		Treatment*Depth	4	0.82	0.523	
	2-3	Treatment	2	0.61	0.553	
		Depth	2	0.11	0.894	
		Treatment*Depth	4	1.31	0.291	
	3-4	Treatment	2	2.16	0.135	
		Depth	2	2.16	0.135	
		Treatment*Depth	4	1.04	0.406	
	4-5	Treatment	2	1.00	0.381	
		Depth	2	1.00	0.381	
		Treatment*Depth	4	1.00	0.425	
P. elegans	0-1	Treatment	2	0.81	0.453	
		Depth	2	0.03	0.969	
		Treatment*Depth	4	0.73	0.578	
	1-2	**Treatment**	2	19.49	**<0.001**	1, 2
		Depth	2	0.86	0.433	
		Treatment*Depth	4	0.67	0.616	
	2-3	**Treatment**	2	16.71	**<0.001**	1, 2
		Depth	2	0.27	0.768	
		Treatment*Depth	4	0.45	0.772	
	3-4	**Treatment**	2	4.19	**0.026**	1
		Depth	2	0.50	0.612	
		Treatment*Depth	4	0.50	0.736	
	4-5	**Treatment**	2	3.37	**0.049**	-
		Depth	2	1.01	0.378	
		Treatment*Depth	4	1.01	0.421	
T. benedii	0-1	Treatment	2	0.45	0.645	
		Depth	2	0.13	0.879	
		Treatment*Depth	4	0.17	0.952	
	1-2	Treatment	2	2.52	0.099	
		Depth	2	0.49	0.618	
		Treatment*Depth	4	0.87	0.493	
	2-3	**Treatment**	2	4.15	**0.027**	1
		Depth	2	0.03	0.967	
		Treatment*Depth	4	1.02	0.413	
	3-4	Treatment	2	0.87	0.430	
		Depth	2	0.38	0.690	
		Treatment*Depth	4	0.80	0.537	
	4-5	Treatment	2	2.05	0.148	
		Depth	2	0.18	0.839	
		Treatment*Depth	4	1.42	0.256	

Bold value indicates significant at 0.05. * Refers to treatments that were found to be significantly different from the control (Tukey's multiple comparison test, $p < 0.05$) '1' indicates mud treatments and '2' indicates sand treatments. ("-" In F & *P* columns denotes zero abundance).

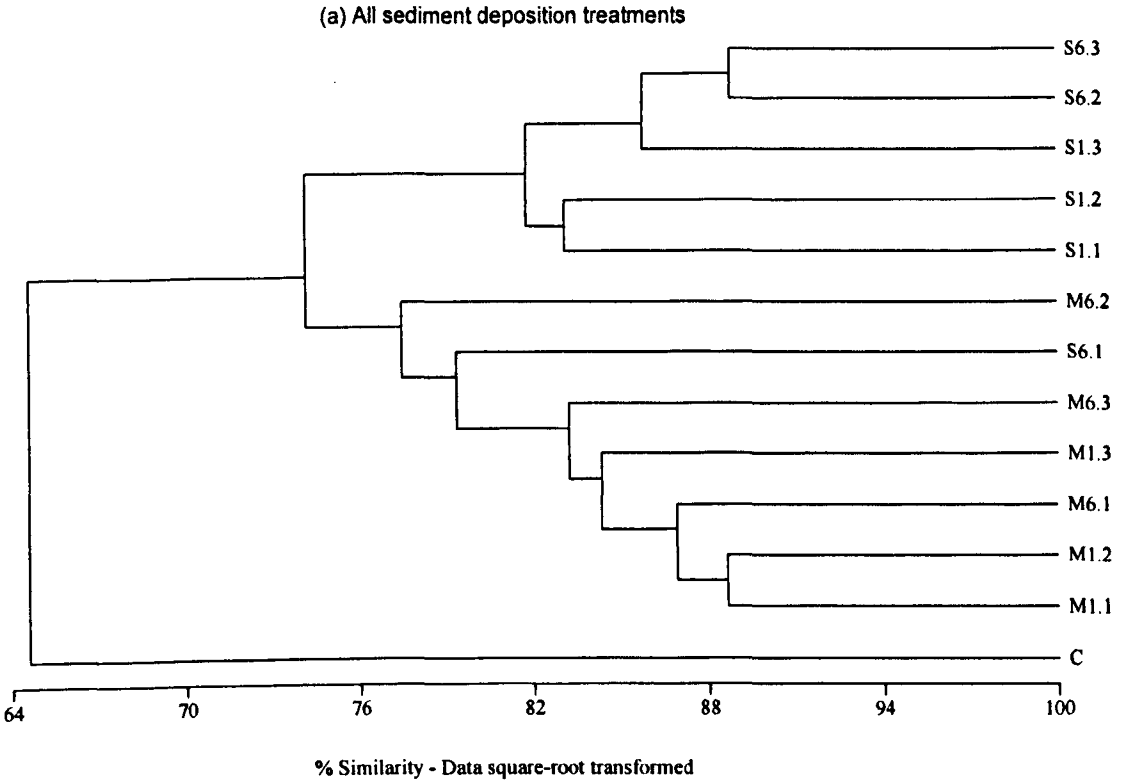
Treatment types of mud or sand placed as a low frequency deposition were significant factors for *A. tenuis, P. elegans* and *T. benedii* (Table 2.4) and also high frequency depositions were significant factors for *A. tenuis* and *P. elegans* (Table 2.5). Therefore, both treatment types placed as a low or high frequency deposition did have a significant effect on the vertical distribution of *A. tenuis* and *P. elegans* and the H_{02} was rejected. However, the low frequency deposition of mud was a significant factor for the vertical distribution of *M. balthica* when migrating to layer 3-4 cm and the high frequency deposition treatments types of mud and sand did not have a significant affect ($P>0.05$) on the vertical distribution (Table 2.5) and hence the H_{02} was accepted. A mud treatment is more often significantly different to the control than a sand treatment. Larger single depositions of treatments had more frequent significant differences between treatments and the control than smaller high frequency depositions of treatments (Tables 2.4, 2.5). Depth and an interaction of depth and treatment were not significant factors for each species (Tables 2.4, 2.5) and so the H_{02} is accepted. Therefore, treatment type did significantly affect the vertical migration of *A. tenuis, P. elegans, and T. benedii.* However depth and an interaction between depth and treatment did not significantly affect the vertical migration of *A. tenuis, M. balthica, P. elegans* and *T. benedii.*

2.3.2 Multivariate analysis

Cluster analysis revealed that all sediment treatment communities were divided into three groups (Figure 2.6 a). The first group consisted of all sand treatments except the high frequency deposition treatment to a depth of 10 cm (S6.1). Within the first group the most similar communities occurred in the high frequency depositions of sand treatments to a depth of 15 cm and 20 cm. The second group consisted of all the mud treatments and the high frequency deposition treatment of sand to a depth of 10 cm (S6.1). In the second group the low frequency deposition treatments of mud to a depth of 10 cm and 15 cm were most similar. The control was placed alone into the third group and was least similar to groups one and two.

The cluster analysis of all low frequency deposition treatments revealed the sand treatments placed to a depth of 10 cm, 15 cm and 20 cm were grouped together (Figure 2.6 b). The macro-faunal communities of the sand treatments with a deposition depth of 15 cm and 20 cm were similar. A second group consisting of all mud treatments revealed the macro-faunal communities of fine-grained sediment treatments placed with a deposition depth of 10 cm and 15 cm were more similar than the 20 cm deposition depth treatment. The control community was least similar to groups one and two.

Cluster analysis of all high frequency depositions of sediment treatments revealed that the macro-faunal communities of the sand treatments deposited in smaller amounts to a depth of 15 cm and 20 cm were similar (Figure 2.6 c). A second larger group consisted of all high frequency depositions of mud treatments and the high frequency deposition sand treatment to a depth of 10 cm. Within group two the macro-faunal communities of high frequency depositions of mud treatments to a total depth of 10 cm and 15 cm were more similar. Again the control was placed into a third group and was least similar to the treatments.



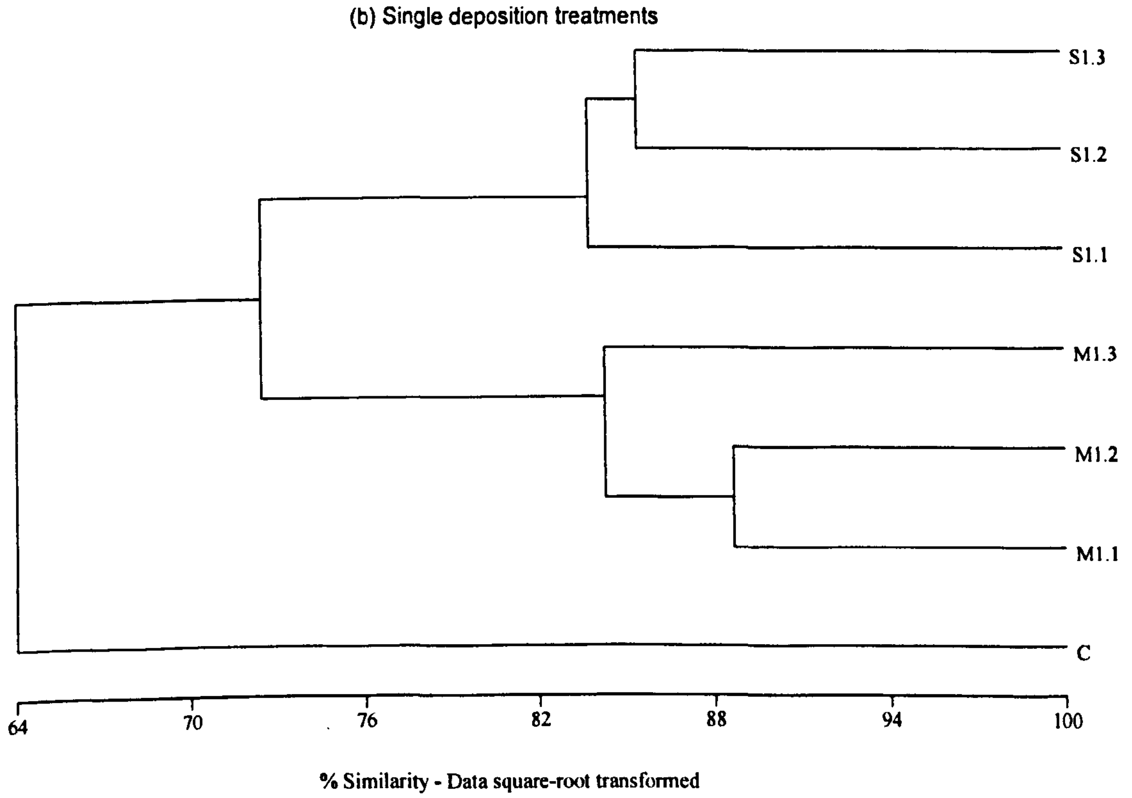


Figure 2.6 (a-c): Assemblage composition similarity dendrogram of all experimental sediment treatments and the control (0-11 cm depth).

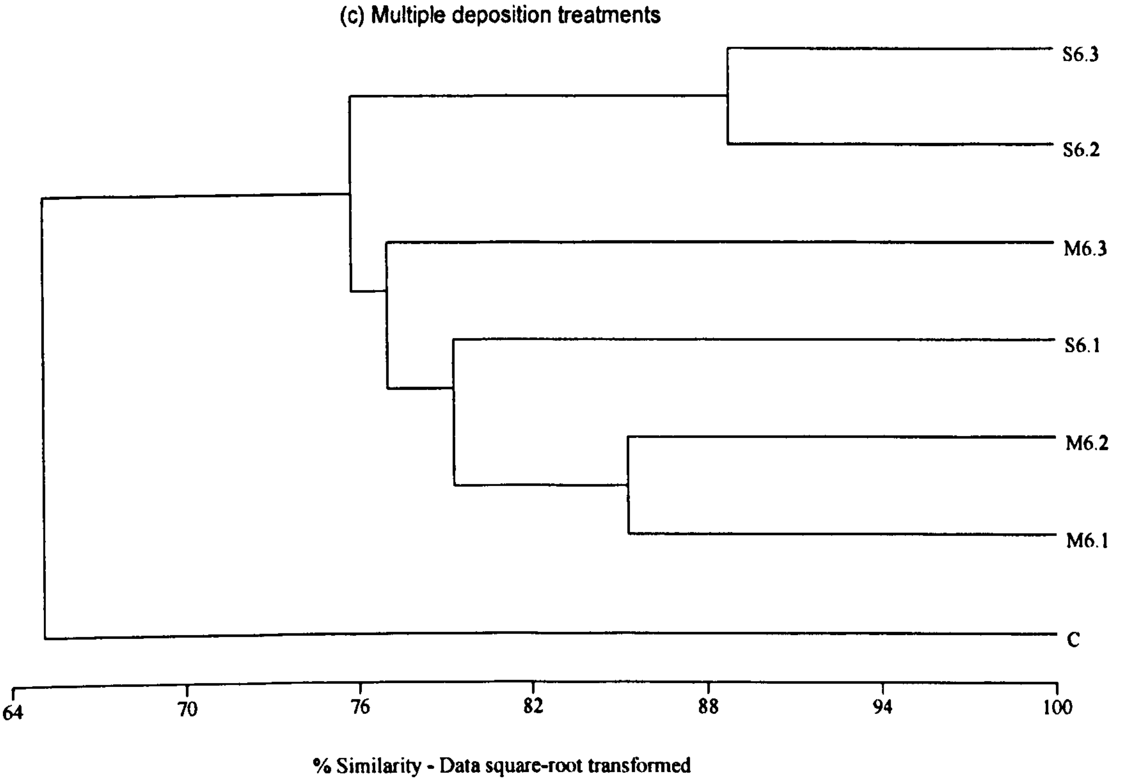


Figure 2.6 (a-c) continued: Assemblage composition similarity dendrogram of all experimental sediment treatments and the control (0-11 cm depth).

2.4 Discussion

Animals present within a recharge site or experimental microcosms may have to adapt their position continuously by vertically migrating into the changing levels of sediment. This was demonstrated in the experimental sediment treatments where some degree of macro-faunal recovery occurred but did not reach the abundance of the mudflat control community. For example, the total individuals in the 10, 15 and 20 cm low frequency depositions of mud and sand were 88 and 83 respectively and the high frequency depositions of mud and sand were 71 and 75, when compared to the control (98). The mud treatment's species richness were equal to or greater than the control and sand treatments, conversely the sand treatments species richness were equal to or less than the control. The control and sand treatments communities were more diverse and had a greater evenness when compared to the mud treatments. Additionally, the high frequency mud deposition treatment communities were more diverse than the low frequency mud treatment communities. Therefore, smaller multiple depositions of mud treatment to a total depth of 10, 15 and 20 cm were colonized more successfully by macro-fauna than when a larger single amount of dredged material was placed to the same depth. According to Maurer, *et al.*, (1980-1981, 1982), several taxa including polychaetes, molluscs and crustaceans are expected to successfully re-colonize dredged material disposal sites by vertical migration. As shown here, burial was achieved by examining the effects of placing different rates and frequencies of simulated dredged material on a sediment base of 10–15 cm depths. Maurer, *et al.*, (1980-81, 1981, 1982) carried out investigations on macro-faunal assemblages including up to three species of the above three faunal groups and concluded all species were able to withstand burial. The vertical migration ability of each individual into an overburden of up to 40 cm of simulated dredged material including a native fine-grained type and/or an exotic sand type, at both summer and winter temperatures, was assessed (Maurer, *et al.*, 1980-81, 1981, 1982). Similarly, Essink (1999) determined a sediment deposition of up to 30 cm is the maximum depth species from a muddy and sandy environment can tolerate, whereas different taxa have been noted to migrate vertically into a sediment overburden of 15 cm (Roberts, *et al.*, 1998; Smith and Rule, 2001). For example, Smith and Rule (2001) investigated maintenance dredged material deposition added as repeated thin layers at a dredged spoil dumping site offshore from a beach in the Solitary Islands Marine Park, Australia. They concluded that the deposition of dredged spoil had no discernible effects on the invertebrate community structure or the physical sedimentary characteristics of the receiving area. Smith and Rule (2001) postulated that several factors were responsible for the minimal impact at the receiving area including, the dredged spoil was analogous to the receiving area and free of contaminants. Also, the method of disposal allowed motile species of the existing benthic community to vertically migrate into the repeated deposition of dredged material and lastly the disposal ground was a high-energy soft-sediment area, thus the resident benthic invertebrate community were likely to be adapted to an unstable environment with periods of sediment erosion and deposition. Similarly, French (1997) used thin-layer depositions, where a total deposition of 12 cm was the maximum compensatory level achieved by benthic fauna.

As shown in the present study, the vertical profiling of the sediment cores provide an indication of the ability of each species to vertically migrate through the sediment depositions and is a technique used in other studies (Maurer, *et al.*, 1980-81, 1982; Davey and Partridge, 1998; Schratzberger, *et al.*, 2000a, 2000b; Sharpless, 2000; Bolam, 2000a, 2003; Bolam and Fernandes, 2002). However, the method used to extract individual species is regarded as stressful and could be an impact in itself.

2.4.1 Macro-faunal vertical migration into soft sediments and species morphology

Some infaunal species of this study such as the tellinid bivalve *M. balthica* and the tubificid oligochaete *T. benedii* showed an innate burrowing ability and are better adapted for upward migration through the sediment matrix of an overburden, an attribute necessary in order to re-occupy pre-burial positions near to the sediment-water interface (Chandrasekara and Frid, 1998; Elliott, *et al.*, 2000). The ability of individual species to overcome burial by vertical migration may be related to the mode of life and the escape ability of an individual may be related to species morphology, for example, the ability of *M. balthica* to vertically burrow through soft sediments is owed to a well-developed cylindrical foot that probes into the sediment grains before swelling to form an anchor, McLusky (1989) describes the burrowing behaviour of mobile bivalve species present in soft sediment environments. Some mollusc species such as *M. balthica* are able to successfully migrate through soft sediments (Hiddink, *et al.*, 2002). Within the vertical profiles of the control and most experimental sediment treatments of this study, *M. balthica* was significantly greater in abundance at the surface than at increased depths (except the low frequency mud deposition to a depth of 20 cm (M1.3)). A bimodal distribution was noted within the vertical profile of this treatment and was due to an increase in sediment veneer depth when the sediment core was vertically profiled, for example, the top 5 cm were sectioned into 1 cm depths and the deeper layers into 3 cm veneer depths. The mean abundances were higher in the surface layers of the mudflat control and sediment treatments and decreased with depth in all low frequency sand treatments. Additionally, vertical migration was widespread within the low frequency mud treatments and was bimodal in distribution. When the vertical distribution of *M. balthica* in the sediment treatments was compared to the control, it was noted that it's vertical migration was not affected by the deposition of low frequency sand treatments and the distribution did not significantly differ to the control. However, the vertical distribution in the low frequency mud treatments was significantly different to the control but only in the layer 3-4 cm. In the high frequency sand deposition of 10 cm (S6.1) mean abundances were higher in the surface layers when compared to the control. When the vertical distribution of *M. balthica* in all high frequency sediment treatments was compared to the control, it was noted that vertical migration was not affected by the type of high frequency treatment and was not significantly different to the control. Therefore, *M. balthica* was successful in upward migration through sand and most mud treatments when deposited at a depth of 10, 15 or 20 cm and was more widespread in distribution in the mud treatments.

Other burial studies have shown that bivalves are able to reach the surface layers of sediment treatments, for example, Maurer, *et al.*, (1980-81) noted that *Mercenaria mercenaria* (Linnaeus) reached the surface layers of 16 cm and 32 cm sand treatments and 32 cm mud treatment following 8 days of burial at winter temperatures, although the percentage abundance was higher in the surface layers of sand. The distribution of *M. balthica* in the present study was similar although its vertical distribution in the mud treatments was more widespread than in the sand treatments. Maurer, *et al.*, (1980-81) study shows the greatest depth colonized (32 cm) exceeds the present study sediment depths (of 10, 15 and 20 cm) used for the mud and sand experimental treatments by at least 12 cm, similarly both studies were conducted at winter temperatures. In comparison, *Nucula proxima* (Say) reached the surface layers of 8 cm and 16 cm when a sediment overburden of 50% silt/clay was placed at summer temperatures (Maurer, *et al.*, 1980-81).

Species with well-developed locomotary parapodia are able to migrate vertically. For example, Sharpless (2000) concluded the errant polychaete *H. diversicolor* was able to reach the surface layers of all experimental treatments of fine-grained sediment when deposited as larger single or smaller multiple amounts to a depth of 1-10 cm in laboratory microcosms at summer temperatures. Sharpless (2000) examined the rate and frequency of simulated fine-grained dredged material deposition (these factors had not previously been investigated thoroughly), by placing a single deposition of simulated fine-grained dredged material to a depth of: 1 cm, 3 cm and 6 cm and secondly using a thin-layer deposition technique by placing several smaller amounts of 2 cm sediment depositions to a total depth of 2 cm, 4 cm, 6 cm, 8 cm and 10 cm. Unfortunately, the overall *H. diversicolor* abundance was low in the mudflat cores of the current study, making it difficult to detect statistical differences due to vertical migration in the experimental sediment treatments. Other Nereid polychaete species are known to burrow upwardly through a soft sediment deposition. For example, Maurer, *et al.*, (1982) noted the vertical distribution of *Nereis succinea* (Leuckart) within sediment treatments varied with sediment type and time. Miller, *et al.*, (2002) investigated the burrowing ability of certain sand flat species present along the Delaware shoreline when simulated sand dredged material was deposited as thin layers and single larger amounts into experimental laboratory microcosms. They noted the infaunal red-gilled polychaete, *Marenzelleria virdis* (Verrill) reached the surface layers of simulated sand dredged material when 5 cm of sediment was deposited onto laboratory microcosms and activities such as tube-building and feeding were not affected by this amount of sediment deposition. However, the expenditure of energetic costs during adaptation to increased sedimentation rates and/or erosion may prove fatal (Brey, 1991), especially for species of low mobility or tube-builders that live and/or feed in the sediment horizon, such as in a shallow sediment depth or at the sediment-water interface (Brenchley, 1981; Brey, 1991). For example, Miller, *et al.*, (2002) concluded the sessile reef-forming *Sabellaria vulgaris* (Verrill), a common lower shore tube-building species along the Delaware shoreline was adversely affected by a 2 cm deposition of sand. However, some individuals were able to reach the surface when a smaller sand deposition of 0.5 cm to 1 cm was placed onto laboratory microcosms.

In the present study, the distribution of *P. elegans* a tube-dwelling spionid polychaete in the vertical profile of the low frequency deposition of mud to a depth of 10 cm and all low frequency deposition treatments of sand (10 cm, 15 cm and 20 cm) were greater in abundance at the surface layers than the deeper layers. It was noted that all individuals did migrate vertically into the sediment treatments from the base mudflat cores. These results suggest that *P. elegans* had a low ability to migrate vertically into the surface layers of low or high frequency depositions of mud when an overburden amount exceeds 15 cm or when smaller high frequency depositions of sand are placed to a depth of 10cm to 20 cm. These results support the experimental field investigations of Bolam (2003) in which a poor vertical migration response of the spionid polychaete *Streblospio shurbsolii* (Buchanan) was noted in sediment treatments of single depositions of 6 cm and 16 cm depths. Both *P. elegans* and *S. shurbsolii* are sedentary tube-dwelling deposit-feeders and showed poor vertical migratory ability into mud treatments in this study.

In contrast, species with jointed appendages had higher survival rates when thin veneer sediment depositions occurred as opposed to a larger single deposition (Brenchley, 1981). In this study, the common mudflat crustacean amphipod *Corophium volutator* (Pallas) was absent and no other crustacea were present. Instead, the Tubificid oligochaete *T. benedii* was the dominant taxon in this study and was distributed over a wider depth, especially in the mud treatments. This may suggest some individuals experienced more difficultly whilst upwardly migrating into a fine-grained sediment overburden or that a wider depth of distribution within the vertical profile of a native fine-grained sediment type was preferable. However, its distribution in some layers of the low- and high-frequency depositions of mud were significantly lower or higher then the control and fewer significant differences occurred when high frequency thin veneers of mud treatment were deposited to a total depth of 10 to 20 cm. This widespread distribution supports the results of Bolam (2003) in which *T. benedii* was distributed throughout the upper 8 cm of the vertical profile in natural sediments and experimental sediment treatments to a depth of 6 cm and was most abundant within the surface treatment layers. Some individuals migrated vertically into the surface layers of the 10, 15 and 20 cm depth sand treatments, thus *T. benedii* had a good ability to migrate through sand depositions and its distribution was not significantly different to the control. Similarly, Bolam (2003) noted that *T. benedii* reached the surface layers of a 6 cm depth high-sand content treatment although more individuals migrated to the surface layers of a 6 cm depth low organic fine-grained sediment treatment. Migration into the surface layers of sediment treatments appears less difficult for more mobile species such as oligochaetes like *T. benedii* and bivalves such as *M. balthica* in comparison to tube-dwelling polychaetes, for example, *P. elegans* and *S. shrubsolii*. The main findings here can be described in a conceptual model based on the effects of simulated dredged material disposals (Figure 2.7).

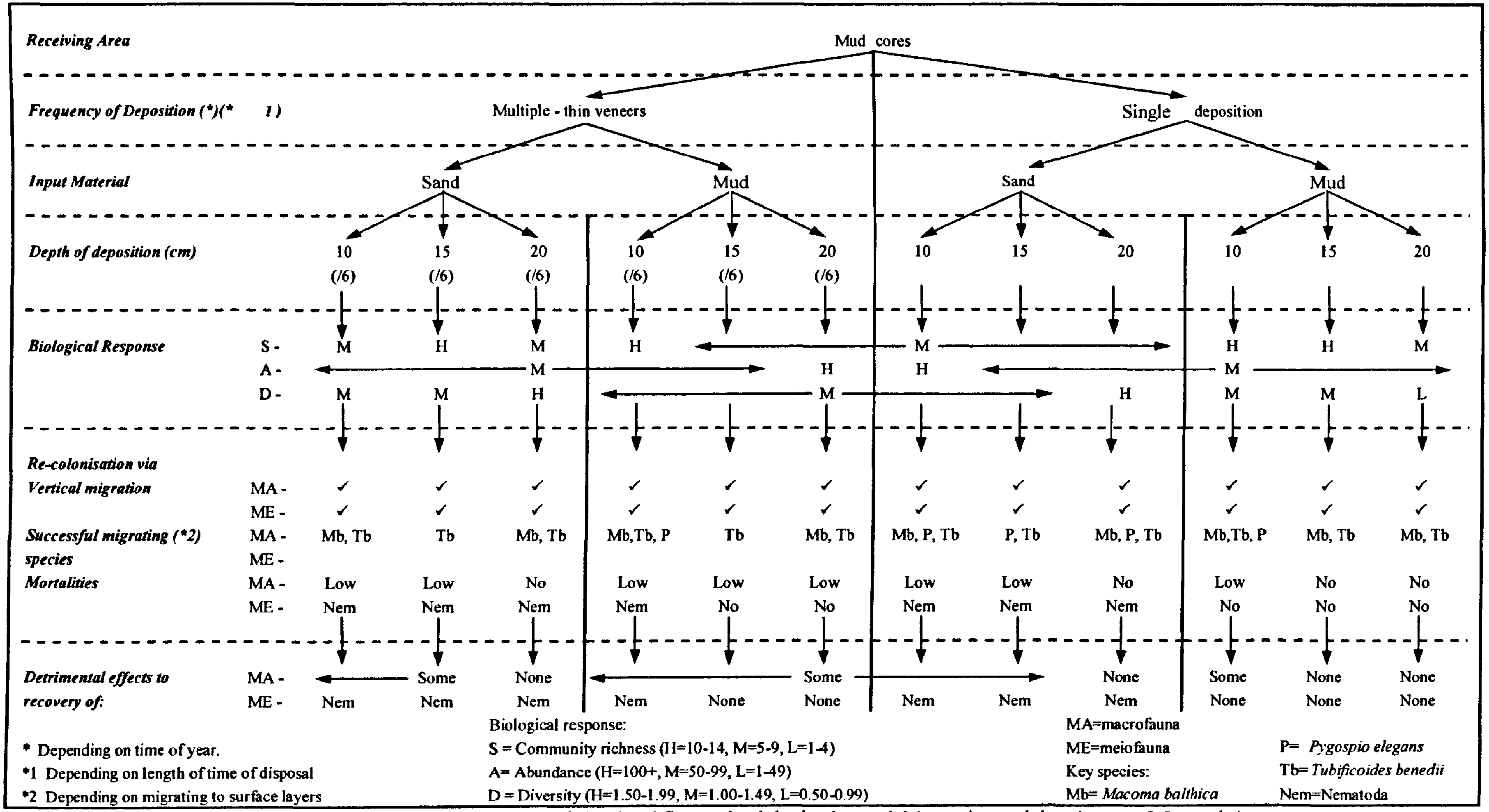


Figure 2.7: Conceptual model of single and multiple depositions of simulated fine-grained dredged material (experimental duration was 2.5 months).

In the present study, nematodes appeared to migrate more into 10, 15 and 20 cm depth of mud treatments when compared to the sand treatments, although an overall low mean abundance was noted. Nematode mortalities were present over a greater depth range when sand treatments were deposited in 10, 15 or 20 cm overburdens, indicating difficulty in migratory ability when compensating for an increased sediment overburden and possibly smothering and asphyxiation may have occurred. Maurer, *et al.*, (1980-81, 1981, 1982) concluded mortalities generally increased with greater burial depth and duration. Nematode species had the greatest mortalities of all species encountered in the present study and nematode mortalities occurred in all sand treatments. Therefore, nematodes appeared more at risk of mortality when a sandy overburden was placed than a fine-grained sediment type. In contrast, the findings of Schratzberger, *et al.*, (2000a) showed that nematodes are capable of vertically migrating to the surface layers when smaller amounts (0.6 cm) of simulated dredged material are placed to a total depth of 6 cm as depositions of native fine-grained sediment treatments or exotic sand treatments. Similarly, a field study using manipulated sediments at an intertidal estuarine mudflat showed the nematode component of a defaunated high-sand sediment treatment had recovered following three months and resembled the natural community of an adjacent mudflat (Schratzberger, *et al.*, 2004a).

2.4.2 Factors affecting macro-faunal survival following burial

Species-specific responses are difficult to compare between laboratory sediment manipulation studies as a number of factors differ (such as key species differences, survival rates, burial depth, sediment treatment type, frequency and amount of sediment deposition, temperature and organic content). Each species will respond differently to burial; for example, the slow colonization of the epifaunal motile gastropod *Hydrobia ulvae* (Pennant) in a fine-grained substratum was linked to a low organic content (Evans, *et al.*, 1998). In contrast, Bolam, *et al.*, (2004) noted a slow recovery in high organic content sediment treatments due to a decreased redox potential. *Hydrobia ulvae* is a surface crawling oblique omnivore and burrows into the mudflat surface at an oblique angle using its foot as an anchor, McLusky (1989) describes the burrowing movement of mudflat snails. The response of *H. ulvae* to successfully vertically migrate into a fine-grained sediment overburden of 6 cm was determined during laboratory (Sharpless, 2000) and field microcosms experiments (Bolam, 2003), although in the current study *H. ulvae* were not common. Similarly, the common Delaware Bay (USA) epifaunal gastropod *Ilyanassa obsoleta* (Say), burrows into the surficial layers of a sand flat and was able to reach the surface layers of between 10 cm and 30 cm of sand deposition in a laboratory microcosm experiment (Miller, *et al.*, 2002). Individuals re-emerged from a single deposition of 10 cm faster than a larger deposition of 30 cm over a 24-hour period and individuals emerged quickly from thin layer sand depositions of 5 cm when placed at 2-hour intervals over an 8-hour period when compared to a single larger placement of 20 cm deposition.

Maurer, *et al.*, (1980-81, 1981, 1982, 1986) noted temperature, sediment mixture, burial depth and duration were determining factors of survival; for example, the upward migration of individuals was more successful during winter temperatures than summer temperatures and could be related to oxygen stress at summer temperatures. Similarly, Sharpless (2000) observed that treatment type; depth of deposition and an interaction of both were determining factors for the vertical distribution of *H. ulvae* and the opisthobranch mollusc *Retusa obtusa* (Montagu). Each macro-faunal species differs widely in its ability to tolerate burial and/or burrow from increased sediment depths and larger mobile adult individuals will be better adapted to withstand burial. The factor treatment and an interaction of treatment and depth did not significantly affect the vertical migration of *H. diversicolor* and *M. balthica* in a separate microcosm study, it appears that their vertical migration ability was not inhibited by the placement of a single amount of fine-grained sediment overburden of up to 10 cm depth (Sharpless, 2000). Though investigations into interactions between species of a faunal assemblage during sediment manipulation studies have been previously overlooked. Chandrasekara and Frid (1998) examined two types of epibenthic gastropod species response to burial during laboratory sediment manipulation experiments. Like Maurer, *et al.*, (1980-81, 1981, 1982, 1986) Chandrasekara and Frid (1998) investigated the ability of each individual to vertically migrate into an overburden of fine-grained sediment deposited to a depth of 5 cm, at winter and summer temperatures using sediment mixtures of high silt-low water (control), high silt-medium water and high silt-high water (fluid mud), the survival rates of each species was recorded. They concluded *H. ulvae* was more tolerant of burial and burial duration when compared to the response of *Littorina littorea* (Linnaeus) a gastropod, to an overburden of different fine-grained sediment treatments. However, the mortality rates of *H. ulvae* were high and fatal for *L. littorea*, in a 5 cm overburden of high silt-low water treatment at increased burial duration and temperature, this treatment included a more consolidated natural mudflat sediment, at winter and summer temperatures. *Hydrobia ulvae* is a soft-bottom sediment-shore species and *L. littorea* is mostly a rocky-shore organism therefore the latter is likely to be less tolerant of sediment burial. In contrast, the mortality rates were low in both test species when a 5 cm overburden of high silt-high water was deposited. Both test species were able to regain a surface position within 24 hours; this low bulk density sediment treatment would be similar to a slurry mixture of dredging disposal, deposited at a sediment recharge site (Bolam and Whomersley, 2005).

Vertical migration was evident throughout the sediment treatments of this study and the migration ability of certain macro-faunal species was more successful than others in different treatments. For example, species such as *M. balthica* and *T. benedii* appeared to find upward migration into a sand type sediment overburden of up to 20 cm depth less difficult when placed as a low- or high-frequency deposition when compared to a fine-grained sediment overburden of 20 cm deposited in as a single amount. Some mean abundances of infaunal species in this study such as *P. elegans* appeared to be greater in exotic sand type treatments when compared to native fine-grained sediment treatments. This agrees with the results of Jackson and James (1979) and Maurer, *et al.*, (1980-81, 1981, 1982, 1986) who concluded that the ability of the faunal assemblage to migrate upward into fine-grained more consolidated native sediment was less than the exotic sandier sediment, therefore the silt content of the sediment was a determining factor (Chandrasedara and Frid, 1998). The particle size analysis and organic carbon content of the experimental sediment treatments was not undertaken in this study. In contrast, some species are sediment-specific, for example, Richards, *et al.*, (1999) noted *Carcinus maenas* (Linnaeus) showed a preference for a muddy sediment type when compared to a sandy substrate.

The present study has shown that some species were more adept than others at re-colonizing simulated dredging disposals. For example, two benthic taxa; *M. balthica* and *T. benedii* did re-colonize simulated dredged material disposals by vertical migration. Others such as *P. elegans* and nematodes were less capable. Therefore, it is necessary to use a suite of benthic macro-invertebrates as indicators of recovery, as recovery may occur at different rates for different species distributions (Moy and Levin, 1991). Even though this is an experimental study, it replicated field conditions by using a natural community structure. However, species abundance may have been too low for certain taxa to show any statistically accurate differences, for example, the bivalve *A. tenuis* and Nematoda. Despite this, the findings here are valid given that all mudflat cores were taken randomly in order to provide a true representation of the distribution of a macro-zoobenthic community at a receiving site of a recharge scheme. The specific species exhibited a high ability to compensate for burial via upward migration into the thin veneer fine-grained or sand sediment depositions and larger single fine-grained or sand sediment depositions to a depth of 10, 15 and 20 cm (Table 2.6) however, there were clear differences of survivorship and migratory abilities between species within the same broad taxon. Indeed Roberts, *et al.*, (1998) suggested such differences of migratory abilities of soft-sediment macro-fauna could highlight potential indicator species for monitoring the impacts of dredge-spoil disposals. It is clear that specific species behavioural responses to sediment burial are not attributed to a single characteristic but a number of causative factors contribute either favourable or detrimentally to the ability of different macro-faunal species to vertically migrate to the surface layers of a sediment overburden. Those factors include sediment grain size, consistency, redox potential, frequency, amount and timing of sediment deposition.

Table 2.6: The survival potential of soft sediment macro-faunal species under different burial conditions in laboratory microcosms.

Species	Burial conditions	Survival depth	Reference
Macoma balthica	Mud treatments deposited at low and high frequencies, at summer temperatures.	1 to 10 cm	Sharpless (2000)
	Mud treatments deposited as a single large amount or thin veneers to a total depth of 10 cm to 20 cm.	20 cm	Present study
	Sand treatments deposited as a single large amount or thin veneers to a total depth of 10 cm to 20 cm.	20 cm	
Mercenaria mercenaria	Sand overburden at winter temperatures for 8 days.	16 cm and 32 cm	Maurer *et al*., (1980-81)
	Mud overburden at winter temperatures for 8 days.	32 cm	"
Nucula proxima	50% silt/clay overburden at summer temperatures.	8 cm and 16 cm	Maurer *et al*., (1980-81)
Hydrobia ulvae	Sediment treatments of high water/low silt/clay and low water/high silt/clay at summer/winter temperatures.	5 cm	Chandrasekara and Frid (1998)
	Mud treatments at summer temperatures.	6 cm	Sharpless (2000)
Ilyanassa obsoleta	Sand depositions.	10 cm and 30 cm	Miller, *et al*., (2002)
Hediste diversicolor	Mud treatments deposited at low and high frequencies, at summer temperatures.	1 to 10 cm	Sharpless (2000)
Nereis succinea	Sand treatments.	90 cm	Maurer *et al*., (1982)
Marenzelleria virdis	Sand deposition.	5 cm	Miller, *et al*., (2002)
Pygospio elegans	Mud treatments deposited as a single large amount or thin veneers to a total depth of 10 cm.	10 cm	Present study
	Sand treatments deposited as thin veneers.	10 cm	
Streblospio shurbsolii	Poor vertical migration response to single depositions of 6 cm and 16 cm depth sediment treatments.		Bolam (2003)*
Sabellaria vulgaris	Sand depositions.	0.5cm and 1 cm	Miller, *et al*., (2002)
Tubificoides benedii	Low organic fine-grained sediment treatment and high-sand content sediment treatment.	6 cm	Bolam (2003)*
	Mud treatments deposited as thin veneers to a to a total depth of 10 cm to 20 cm.	20 cm	Present study
	Sand treatments deposited as a single large amount or thin veneers to a total depth of 10 cm to 20 cm.	20 cm	
Nematoda	Mud and sand treatments deposited as small multiple amounts of 0.6 cm.	6 cm	Schratzberger *et al*., (2000a)
	High mortalities when sand treatments deposited to a depth of between 10 cm and 20 cm.		Present study

Note: * indicates a sediment microcosm field experiment.

This experiment used treatments of mud and sand sediment types and was the first experimental research conducted for this PhD thesis. However, most beneficial use schemes occur on intertidal estuarine mudflats and as part of the licensing process to dispose dredged material as a beneficial use, certain criteria need to be established before a scheme can be implemented. For example, the nature of the disposal material such as the particle size has to be analogous to the receiving environment such as an intertidal mudflat; therefore the results of the mud treatment depositions are more important in this study when considering beneficial use schemes. In comparison, the migratory behaviour of mudflat macro-fauna into exotic sand treatments maybe of value when considering areas of sand flat or sandy beach nourishment, but only those species in this study common to both mud and sand habitat types. The subsequent chapter investigates further the deposition of fine-grained sediment and the ability of infaunal mudflat species to overcome burial by migration through the sediment overburden. Overall, the ability of certain macro-fauna to overcome burial was high when 10 cm, 15 cm or 20 cm of sand or mud treatment was placed in a single low frequency deposition or several smaller amounts to the same depth. However, related studies presented in the following chapter show that at greater depths relationships do exist between the amount of dredged material added and the ability of macro-invertebrates to vertically migrate and survive.

2.5 Conclusions

- Some degree of faunal recovery occurred in the 10, 15 and 20 cm depth sediment treatments but the total mean abundances of most sediment treatments remained lower than the control except when a single deposition of sand treatment to a depth of 10 cm was applied. Overall, the mud treatments had the greatest species richness followed by the control and the sand treatments. The mean diversity and evenness were greatest in the control and sand treatments. Additionally, the high deposition treatments of mud were more diverse than the low frequency depositions.
- *Macoma balthica* was successful in upward migration through sand and most fine-grained sediment treatments when deposited to a total depth of 10, 15 or 20 cm and was more widespread in distribution in the mud treatments.
- *Tubificoides benedii* exhibited an ability to re-colonize the surface layers of sand treatments when deposited in low or high frequencies, but its distribution was more widespread in the mud treatments deposited in low or high frequencies.
- *Macoma balthica* and *T. benedii* appeared to find upward migration into a sand type sediment overburden of up to 20 cm depth less difficult when placed in a low- or high-frequency deposition when compared to a fine-grained sediment overburden of 20 cm deposited as a single amount.
- *Pygospio elegans* could vertically migrate to the surface layers of a 10 cm depth sediment overburden of mud deposited as low or high frequencies or a sand overburden of 10 cm when deposited as a single amount. These results suggest that *P. elegans* had a low ability to migrate vertically into the surface layers of low- or high-frequency depositions of mud when an overburden amount exceeds 10 cm or when smaller high frequency depositions of sand are placed to a depth of 10-20 cm.
- Nematodes appeared to migrate more into mud treatments than sand treatments. Nematodes had the greatest mortalities of all species encountered in this study and appeared more at risk of mortality when a sand overburden was deposited than a mud treatment.
- The results of this study along with similar studies suggest that thin-layer depositions of sand or mud have less detrimental effects on the mudflat macro-fauna when compared to single larger depositions of the same total amount of 10, 15 or 20 cm. However, it is recommended that single depositions of up to 10 cm in depth may be less damaging to benthic macro-fauna than larger 20 cm single depositions.
- The conceptual model highlights the ability of certain macro-faunal species to migrate vertically into simulated dredged material when deposited as thin veneers or single larger amounts when tested under controlled laboratory conditions, further testing of this concept were investigated in field experiments.

3 Macro-faunal vertical and horizontal re-colonization of simulated dredged material

3.1 Introduction

The direct placement of increased amounts of dredged material onto a mudflat may have a detrimental impact on the estuarine benthos. Sudden inputs of any sediment type can result in a large population of a low number of species tolerant of unstable sediment (Elliott, *et al.*, 2000). It is important to determine the nature of the benthic community within the receiving area of a sediment recharge scheme to determine which dominant species can tolerate burial, if the recharge amount exceeds an organism's burrowing and migratory ability, the individual will become smothered (Smith and Rule, 2001) and/or asphyxiated. Fragile species such as those with sensitive limbs or soft bodies will be more susceptible to damage during a recharge operation; similarly, the tubes of tube-building species may become damaged during the operation of placing dredged material. Therefore, re-colonization by the more sensitive species may be limited owing to several life-history traits including late sexual maturity, low fertility and special brood care, low mobility of early life stages. The re-colonizing potential may be further reduced following damage or elimination of a population after a sediment deposition event. Rates of re-colonization are often dependent upon the nature of the adjacent undisturbed mudflat community, which provides a pool of recruits capable of re-colonizing the site by active adult immigration (Zajac and Whitlach, 1982; Alphin and Posey, 2000; Elliott, *et al.*, 2000) or by passive transport. The re-colonization of the dredge disposal material would take place by immigration of benthic fauna from areas next to the recharge site via active horizontal migration (Frid, 1989; Smith and Brumsickle, 1989) and/or vertical migration from below (Jackson and James, 1979; Maurer, *et al.*, 1980-81, 1981, 1982 & 1986; Chandrasekara and Frid, 1998; Smith and Rule, 2001) the recharge site.

3.1.1 Sediment deposition; indirect consequences

Within a created intertidal habitat, the resulting composition of macro-zoobenthos would be different from the original benthic community, indirect effects may be experienced higher up the food chain, where the degree of utilization of the mudflat by birds and/or fish may become reduced and changes in species composition and abundance may occur. However, once a specified mudflat height has been attained, the recharge area begins to stabilise and the length of exposure time will become extended, this will allow increased space and feeding time for birds, hence dredged material can be used to fulfil the functions of natural mudflats.

3.1.2 Sediment deposition; direct consequences

The adjustment of an intertidal mudflat profile would be accomplished relatively quickly by the layering of large quantities of uncontaminated, fine-grained dredged material across the mudflat. In doing so, the shoreline sea defences receive more protection and a recharge site could receive additional replenishment following the effects of a storm event. The complexity of a mudflat ecosystem extends to the sensitivity of the benthic assemblage and will respond to immediate and direct deposition of sediment (Elliott, *et al.*, 2000). Each individual species differs widely in its ability to tolerate burial and/or burrow from increased sediment depths. Survival will depend mainly upon an individual's mobility, size, shape, age, armour and/or shell protection and tolerance of changes in abiotic variables. Larger mobile adult individuals will be better adapted to withstand or avoid burial than juvenile life-stages. The increased fragility of the physical structure of an individual, for example, species with sensitive limbs or soft bodies, will be more susceptible to damage during a recharge operation. Similarly, direct effects to an individual may include damage to the body, for example, the filtration apparatus of filter-feeding zoobenthic species may become smothered during thin veneer sediment depositions, along with the dwelling structure of tube-building species, which may become impacted. Such impacts would be irreversible and only species specific to the recharge substrata composition will predominate, thus altering the nature of an intertidal benthic community indefinitely.

The re-colonization by benthic macro-fauna of previously defaunated intertidal areas has been examined during *in situ* sediment manipulation experiments (Diaz-Castaneda, *et al.*, 1993; Turner, *et al.*, 1997; Bolam, 1999, 2003; Bolam and Fernandes, 2002; Bolam, *et al.*, 2004) and more recently the re-colonization by benthic meio-fauna (Schratzberger, *et al.*, 2004 a). Similarly, Levin (1984) investigated the horizontal migration by benthic macro-fauna into defaunated plots. Bolam and Rees (2003) reviewed a number of dredged material disposal areas of the United States coastal environment. In addition dredged-material constructed intertidal mudflats have been compared to natural mudflats based on the benthic invertebrate community and sediment characteristics (EA, 1998; Ray, 2000; Bolam and Whomersley, 2003, 2005), thus providing broad-scale information on macro-invertebrate recovery mechanisms. The ability of macro-fauna to vertically migrate into laboratory microcosms containing a sediment overburden of up to 20 cm was described in chapter 2. The deposition of dredged material at the beneficial use schemes in the UK was greater than 20 cm and approximately 60-80 cm of recharge material was placed on the intertidal mudflats (Bolam and Whomserley, 2005). To support the results obtained from chapter 2 and the beneficial use schemes, this study investigates the ability of macro-fauna to vertically migrate into a fine-grained sediment overburden of 50 cm and horizontally migrate into a 27 cm depth of sediment overburden.

3.1.3 Aims, objectives and null hypotheses

A series of field manipulation experiments were conducted on the Skeffling mudflat, along the Humber Estuary. The specific aims of this research were to understand the relationship between the amounts of fine-grained simulated dredged material deposition and macro-faunal re-colonization through vertical and lateral migration, therefore the main focus of this study was directed towards the biological component of the re-colonization experiments. The sediment characteristics of the experimental sediment treatment and the mudflat were not recorded. The main objectives of the study were to compare (a) univariate community characteristics and (b) species composition of re-colonized simulated fine-grained dredged material added as a single low frequency amount to a depth of 50 cm and 27 cm and to suggest which macro-invertebrate species were able to withstand burial and were able to migrate to a natural position within the vertical profile of the defaunated sediment treatment. In particular, the following null hypotheses were tested: (1) univariate community characteristics do not recover over time following a sediment deposition event; (2) macro-faunal re-colonization via vertical migration is not affected by a single low frequency deposition of simulated fine-grained dredged material to a depth of 50cm and (3) macro-faunal re-colonization via horizontal migration is not affected by a single low frequency deposition of simulated fine-grained dredged material to a depth of 27 cm.

3.2 Methods and Materials

3.2.1 Macro-faunal vertical migration

An investigation into the macro-invertebrate re-colonization of simulated dredged material added into tube microcosms, through the vertical migration of macro-fauna at the high shore Skeffling mudflats, was started in November 2001 for a duration of four months. Experiments could not be conducted at the field site during the period between February and October 2001, due to the closure of bridal ways, as a result of the foot and mouth epidemic access to the mudflat was prohibited. Subsequently, this experiment was conducted on a winter macro-zoobenthic assemblage that would differ in species composition and abundance to the spring-summer communities. A manipulated fine-grained sediment treatment was used to examine the effects of a single low frequency deposition of 50 cm simulated fine-grained dredged material and macro-faunal re-colonization via vertical migration. The volume of material added to gain the required simulation depth of 50 cm per microcosm was calculated as 3925 ml.

3.2.1.1 Treatment and control descriptions

To simulate fine-grained dredged material the top 10 cm surface layers were removed from the high-shore area of the Skeffling mudflats. All the material collected (15 x 5 litre (l) containers) was defaunated by sieving through a nest of sieves (with mesh screens of 500 μm to 125 μm) to remove any macro-fauna, juveniles and/or larval stages thus reducing organic material, secondly a freeze-thaw process was used to remove any possible macro-faunal contamination remaining by encouraging the decomposition process. The material was the stored in a chest freezer at –20 °C for 5 days (to ensure the freezing process of the material had taken place), after which each container was removed and thawed at a room temperature of 20 °C for 48 hours (h) (Bolam, 2003; Bolam and Fernandes, 2002; Junkins, *et al.*, 2006). This freeze-thaw process was repeated three times for each sediment batch collected. Following the final freeze-thaw period, the defaunated material was homogenized in a large container to produce the simulated fine-grained dredged material treatment. A total of 15 Perspex tubes (10.4 cm (id) x 1 m height (ht)), used as experimental microcosms, were randomly placed within a 4 m^2 plot, located at the mean high-shore spring tide level at the following co-ordinates: 53 °N 38.525, 000 °E 04.068 (Figure 3.1). Each microcosm was inserted into the mudflat to a depth of 40 cm. Prior to placement, a drainage hole had been drilled into each microcosm tube, above the surface level of treatment deposition, to prevent any standing water occurring. In order to show that vertical migration occurred from the actual mudflat, a piece of 63 μm aperture mesh was secured over the top of each microcosm, which excluded the re-colonization of macro-fauna by settlement from above and thus prevented any animals escaping from within. A single 50 cm deposition of defaunated fine-grained sediment treatment was placed inside each microcosm. Samples were removed after 1, 2, 4, 6 and 10 weeks (wk), each with three replicates. In addition, three replicate control cores (10.4 cm (id), 15 cm depth (d)) were removed from an undisturbed area of mudflat within the experimental site, to assess the nature of the receiving environment in terms of the biological characteristics.

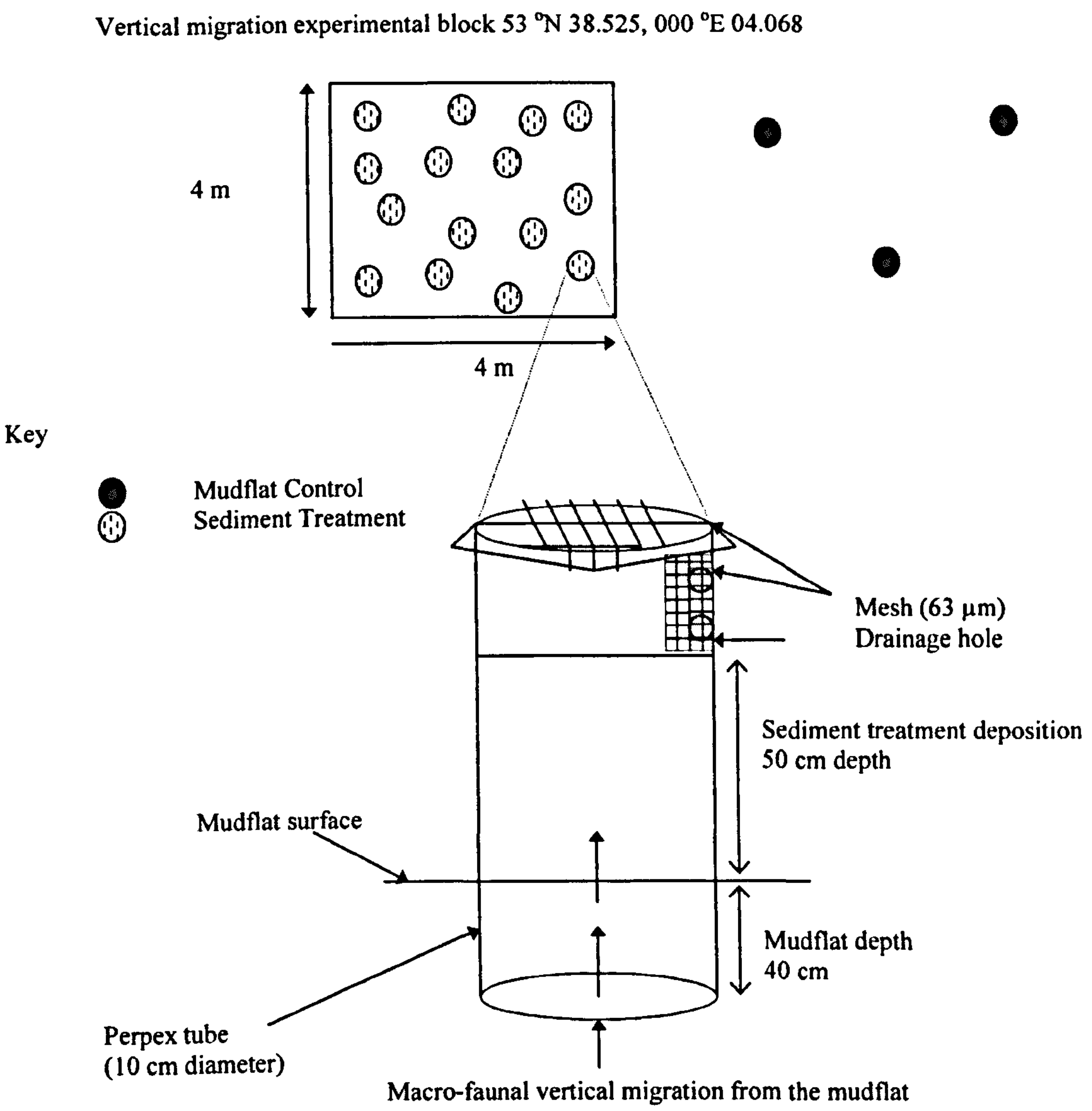


Figure 3.1: Experimental set-up of treatment microcosms (n = 3).

3.2.1.2 Faunal analysis

On each sampling occasion, three replicates of the treatment were removed and the vertical migration of macro-fauna into the sediment overburden was assessed by vertically profiling the mud treatment. Each replicate was sectioned into 3 cm increments *in situ* (from 0-3 cm to 87-90 cm) and stored separately in a labelled plastic sample bag. Upon return to the laboratory each increment was sieved using a 500 μm mesh screen. Using a dissecting microscope any macro-fauna present within each horizontal section were extracted and tested for mortality via the detection of movement and sorted into major taxonomic groups then fixed in 4% formo-saline buffered solution with Rose Bengal vital stain for a minimum of 48 h. Identification was carried out using both dissecting and compound binocular Olympus microscopes and species abundance per horizontal section of each microcosm was recorded. All specimens were preserved and stored in 70% IMS and labelled to include the sampling date, increment number, replicate, taxon and abundance. Samples were randomly chosen for quality control analysis by a second benthic taxonomist employed within the Institute of Estuarine and Coastal Studies.

3.2.2 Macro-faunal horizontal migration

This *in situ* pilot study ran alongside the macro-faunal vertical migration experiment, at the same time and the same mudflat location. The second study included an investigation into the macro-invertebrate re-colonization of defaunated simulated fine-grained dredged material through macro-faunal horizontal migration. An open sided box container, with a closed base to prevent the vertical migration of macro-fauna from below (30 cm d, 40 cm wide (w) and 75 cm length (le)) was inserted into a hollowed area of mudflat to a depth of 27 cm at the following co-ordinates: 53 °N 38.520, 000 °E 04.074 (Figure 3.2). Simulated fine-grained dredged material (described earlier) was placed inside the box container, to a depth of 27 cm and was contiguous with undisturbed mudflat sediments. The volume of material added to gain the required simulation depth per microcosm was calculated as 81 l.

A 63 µm aperture mesh was secured over the top of the experimental plot to act as a barrier and thus prevent macro-faunal migration or settlement from above or escape from within the plot. The horizontal migration of macro-fauna into the simulated dredged material was assessed, by taking core samples (10.4 cm (id)) to a depth of 27 cm. A total number of three replicates were randomly removed from the experimental plot after 4, 14 and 28 days. Following sample removal a plug was inserted into the gap thus preventing the collapse of the sediment profile. Each replicate was sectioned into 3 cm increments *in situ* (from 0-3 cm to 24-27 cm) and processed as described earlier.

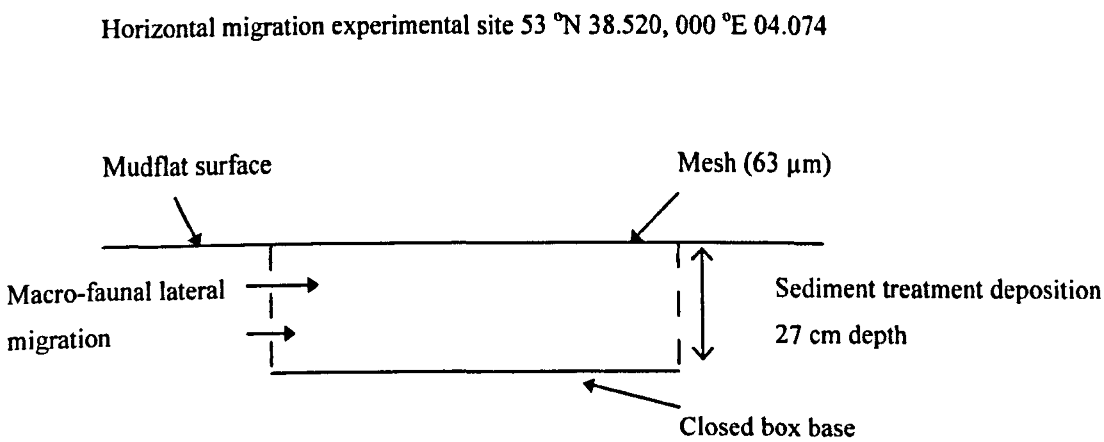


Figure 3.2: Experimental set-up of treatment container ($n = 3$).

These short preliminary field investigations aimed to develop methodological approaches for further experiments to be conducted in the spring/summer seasons. In this instance the mudflat control taken at the beginning of the winter study acted as a benchmark for these initial field experiments. The field manipulation experiments had finished before the beginning of the macro-zoobenthic spring recruitment phase and the potential influx of larvae through the mesh cover was prevented in both experiments due to the small aperture size of the mesh.

3.2.3 Data analyses

The invertebrate data were analysed using both univariate and multivariate techniques. The data were checked for normality using the Kolomogrov-Smirnov test and homogeneity of variances were tested using a Levene's test and descriptive statistics were determined. Any data not conforming to a normal distribution were transformed using a square-root transformation (Zar, 1996). As the same plots were sampled throughout the experiment, there was an increased risk of a type I error being committed resulting in the possibility of non-independence occurring during sampling times. To test the effect of treatment and time on community variables and species abundances, repeated measures analysis of variance tests were performed in which treatment and time were within effect factors. If Mauchly test of spherecity was violated then a Greenhouse-Geisser correction factor was applied to that factor during a within effects repeated measures analysis of variance (Field, 2000). A repeated contrast of between effects was conducted to determine which factor differed to another at each time and treatment. Bonferroni multiple comparison tests were performed to investigate any differences between time and between treatments. All univariate analyses were conducted using SPSS version 13.

The Shannon-Wiener index (H') was used to indicate community diversity. This integrates species richness and relative abundance (Barker, *et al.*, 1987) and high values indicate high diversity, whilst low values indicate low diversity. Pielou's evenness index (J') was used to give a measure of the relative abundance of each species. A low diversity is expressed as a low J' value and indicates a community is dominated by one or few species, a situation which often occurs in low diversity areas subject to disturbance. A more diverse community where there is an even spread of individuals between the species is expressed as a J' value closer to 1. Both univariate indices (H' and J') were performed using MVSP version 3.12a. Multivariate classification analysis (cluster analysis) of the data was undertaken using the Bray-Curtis similarity coefficient and group average (UPGMA) clustering technique. Cluster analysis was performed on species composition to assess (dis) similarities between community assemblages of the control and treatments. The similarity between the control and treatments was calculated using the Bray-Curtis similarity coefficient to produce a similarity matrix showing the percent similarity of groups (0 % indicating no species in common and 100 % indicating an identical community). A dendrogram was used to illustrate the relative importance of control and the treatment type on community structure, consequently it is possible to define groups of sites with similar species composition at a predefined level of similarity. All multivariate analyses were performed using MVSP version 3.12a.

3.3 Results

3.3.1 Macro-faunal vertical migration

In total 1411 individuals were sampled from 8 taxa from all microcosms. A total of 1080 individuals were sampled from the control and 332 from the treatment with a total of 5 and 8 taxa being sampled from the control and treatment respectively. Nematoda had the greatest total abundance of 741 individuals although most (736) were present in the control and few had colonized the treatment (5). The Tubificid oligochaete *Tubificoides benedii* (Udekem) total abundance was 452, an equal number of individuals were present in the control and the treatment with 231 and 221 individuals respectively. *Macoma balthica* had the third highest total abundance of 153 individuals, with 99 individuals sampled from the control and 54 from the treatment, Tellinacea juveniles (j) had a total abundance of 25 however only 3 individuals were sampled from the control and 22 individuals had colonized the treatment. Similarly, the gastropod mollusc *Hydrobia ulvae* (Pennant) was absent in the control but 21 individuals had colonized the treatment microcosms. Few *Abra tenuis* (Montagu) a tellinid bivalve mollusc, the polychaetes *Eteone longa/flava* agg (Fabricius) and *H. diversicolor* had colonized the treatment microcosms. Overall the control had the greatest total abundance of individuals (1080) sampled on day 1, followed by wk 2 treatment microcosms (114), wks 1 and 6 had a similar total abundance of 107 and 90 respectively, wks 4 and 10 were low in total abundance (12 and 9 respectively).

The mudflat control had the highest mean abundance of total individuals (360) overall when compared to the treatment microcosms (Figure 3.3 a) although the mean abundances were similar during wks 1 (36), 2 (38) and 6 (30), yet minimal during wks 4 and 10. The treatment microcosm sampled at wk 1 had the highest species richness of 8 followed by the treatment microcosms taken at wks 2 and 6 with 6 and 5 species respectively similarly, the control had species richness of 5. A total of 3 species were sampled from the treatment microcosms at wks 4 and 10 (Figure 3.3 b). Overall species diversity was greatest in the treatment microcosm of wk 2 and least during wk 4, the control and treatment microcosms from wks 1, 6 and 10 were similar (Figure 3.3 c). Pielou's evenness was highest in the treatment microcosm of wk 4, followed by wks 10 and 2; wk 6 had a similar evenness to the control (Figure 3.3 d).

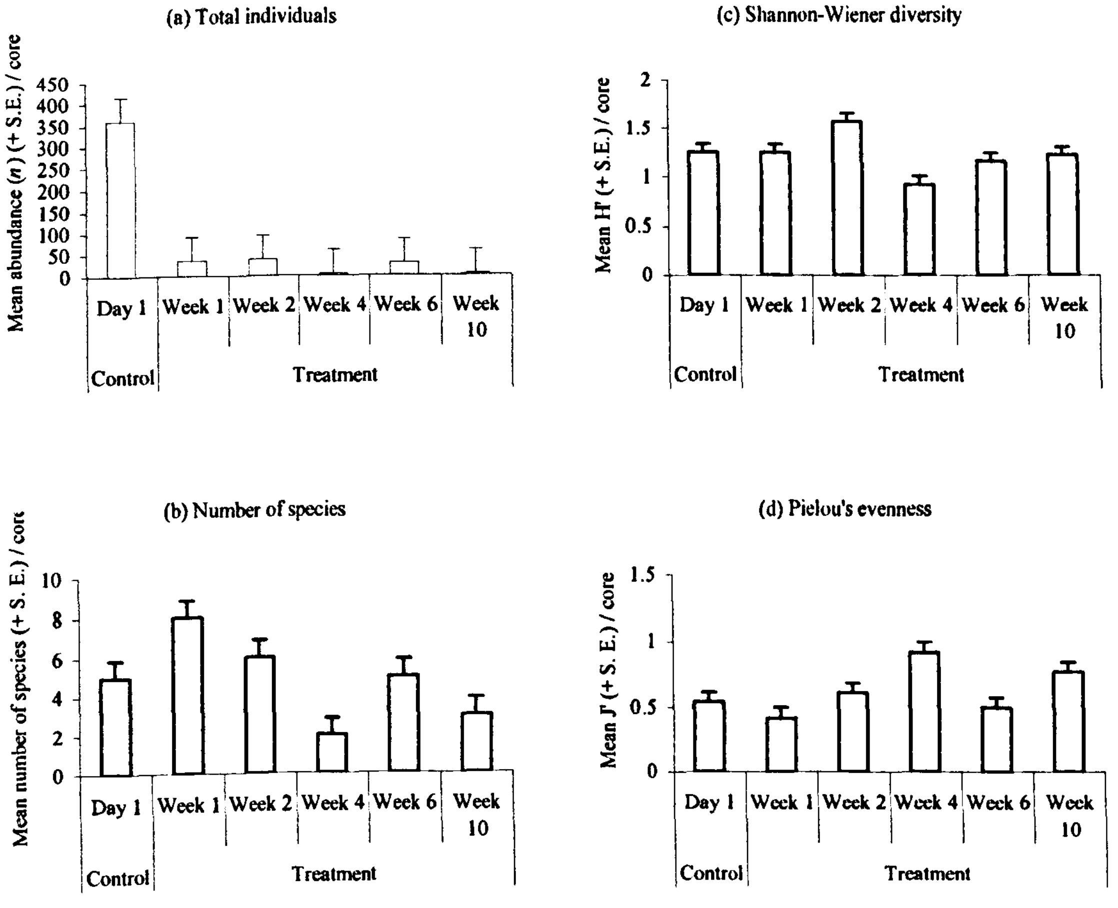


Figure 3.3 (a-d): Univariate indices of macro-fauna in the control and treatment (+ S.E., n = 3) per core per sampling occasion.

Most individuals present within the control were in the surface layers of the mudflat; the layer 0-3 cm was especially high 337 individuals recorded (Figure 3.4 a). In total 94 % of total individuals present in the control were in layer 0-3 cm and a further 5 % in layer 3- 6 cm (Figure 3.4 b). At wk 1 some colonization of macro-fauna in the treatment microcosms had occurred and the vertical migration of total individuals of 16 was greatest at the depth 39-42 cm from the treatment surface by vertically migrating through at least 9 cm of sediment overburden (Figure 3.4 a). By wk 2, a greater number of total individuals had vertically migrated into the surface layers and were present throughout layers 3-6 cm to 42-47 cm (Figure 3.4 a). The greatest cumulative percentage of macro-fauna colonizing the treatment microcosms at wk 2 occurred in layers 36-39 cm to 39-42 cm (73 % and 95 % respectively) (Figure 3.4 b). By wk 4 some macro-fauna had vertically migrated to the surface layer of the treatment, although colonization was generally low (Figure 3.4 a-b). At wk 6 the macro-fauna colonizing the treatment were distributed throughout the microcosms and those reaching the surface layers had vertically migrated through a minimum of 50 cm of sediment overburden (Figure 3.4 a). At wk 6 a cumulative abundance of 50 % of macro-faunal individuals were distributed between layers 0-3 cm to 21-23 cm (Figure 3.4 b). Few individual macro-fauna had vertically migrated into the sediment treatment at wk 10 (Figure 3.4 a), therefore the cumulative percentage of total individuals in the sediment treatment at wk 10 was out of sequence when compared to the earlier sampling occasions (Figure 3.4 b).

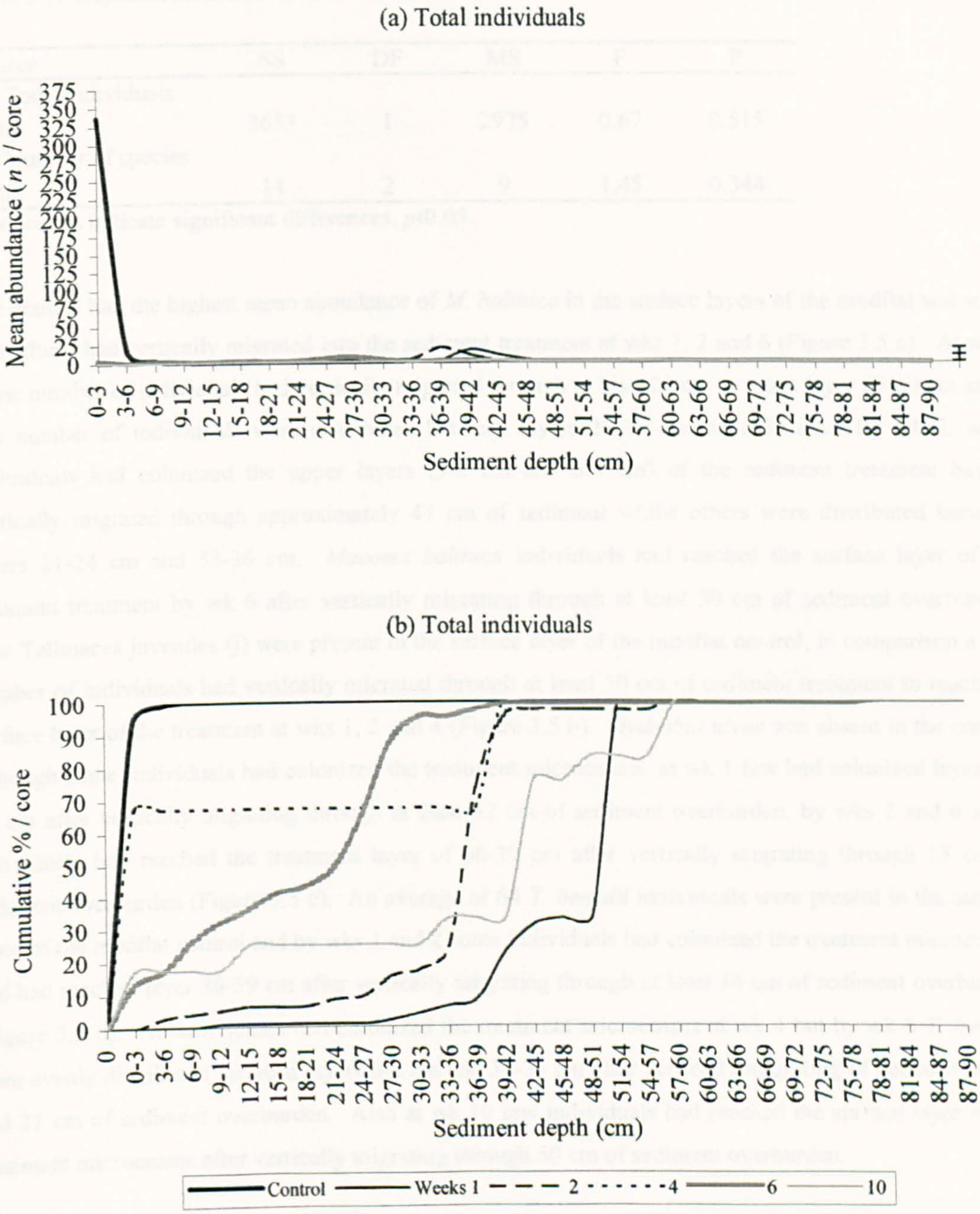


Figure 3.4 (a-b): Mean abundance ($n = 3$) and cumulative percentage of total individuals per layer. Error bars at the bottom of figure (a) denote (±) pooled Poisson confidence intervals.

The mean abundance of total individuals and species richness of the treatment microcosms were not significantly different between time when comparing a repeated measures analysis of variance between wks 1, 2, 4, 6 and 10 (Table 3.1) however an influx of macro-faunal colonization of the sediment treatment by vertical migration from the original mudflat did occur within time but mean abundances did not reach those recorded in the control at day 1 (Figure 3.4 a).

Table 3.1: Repeated measures ANOVA of univariate indices of macro-fauna in the treatment.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time	3653	1	2975	0.67	0.515
(b) Number of species					
Time	14	2	9	1.45	0.344

Bold values indicate significant differences, $p<0.05$.

The control had the highest mean abundance of *M. balthica* in the surface layers of the mudflat and some individuals had vertically migrated into the sediment treatment at wks 1, 2 and 6 (Figure 3.5 a). At wk 1 a low number of individuals had vertically migrated through at least 23 cm to reach layer 27-30 cm and a low number of individuals were distributed between layers 27-30 cm to 36-39 cm. By wk 2, some individuals had colonized the upper layers (3-6 cm and 6-9 cm) of the sediment treatment having vertically migrated through approximately 47 cm of sediment whilst others were distributed between layers 21-24 cm and 33-36 cm. *Macoma balthica* individuals had reached the surface layer of the sediment treatment by wk 6 after vertically migrating through at least 50 cm of sediment overburden. Few Tellinacea juveniles (j) were present in the surface layer of the mudflat control, in comparison a low number of individuals had vertically migrated through at least 50 cm of sediment treatment to reach the surface layer of the treatment at wks 1, 2 and 4 (Figure 3.5 b). *Hydrobia ulvae* was absent in the control although some individuals had colonized the treatment microcosms, at wk 1 few had colonized layer 18-21 cm after vertically migrating through at least 33 cm of sediment overburden, by wks 2 and 6 some individuals had reached the treatment layer of 36-39 cm after vertically migrating through 15 cm of sediment overburden (Figure 3.5 c). An average of 64 *T. benedii* individuals were present in the surface layer of the mudflat control and by wks 1 and 2 some individuals had colonized the treatment microcosms and had reached layer 36-39 cm after vertically migrating through at least 14 cm of sediment overburden (Figure 3.5 d). No individuals had colonized the treatment microcosms at wk 4 but by wk 6 *T. benedii* were evenly distributed between layers 0-3 cm and 30-33 cm after vertically migrating of between 50 cm and 21 cm of sediment overburden. Also at wk 10 few individuals had reached the surface layer of the treatment microcosms after vertically migrating through 50 cm of sediment overburden.

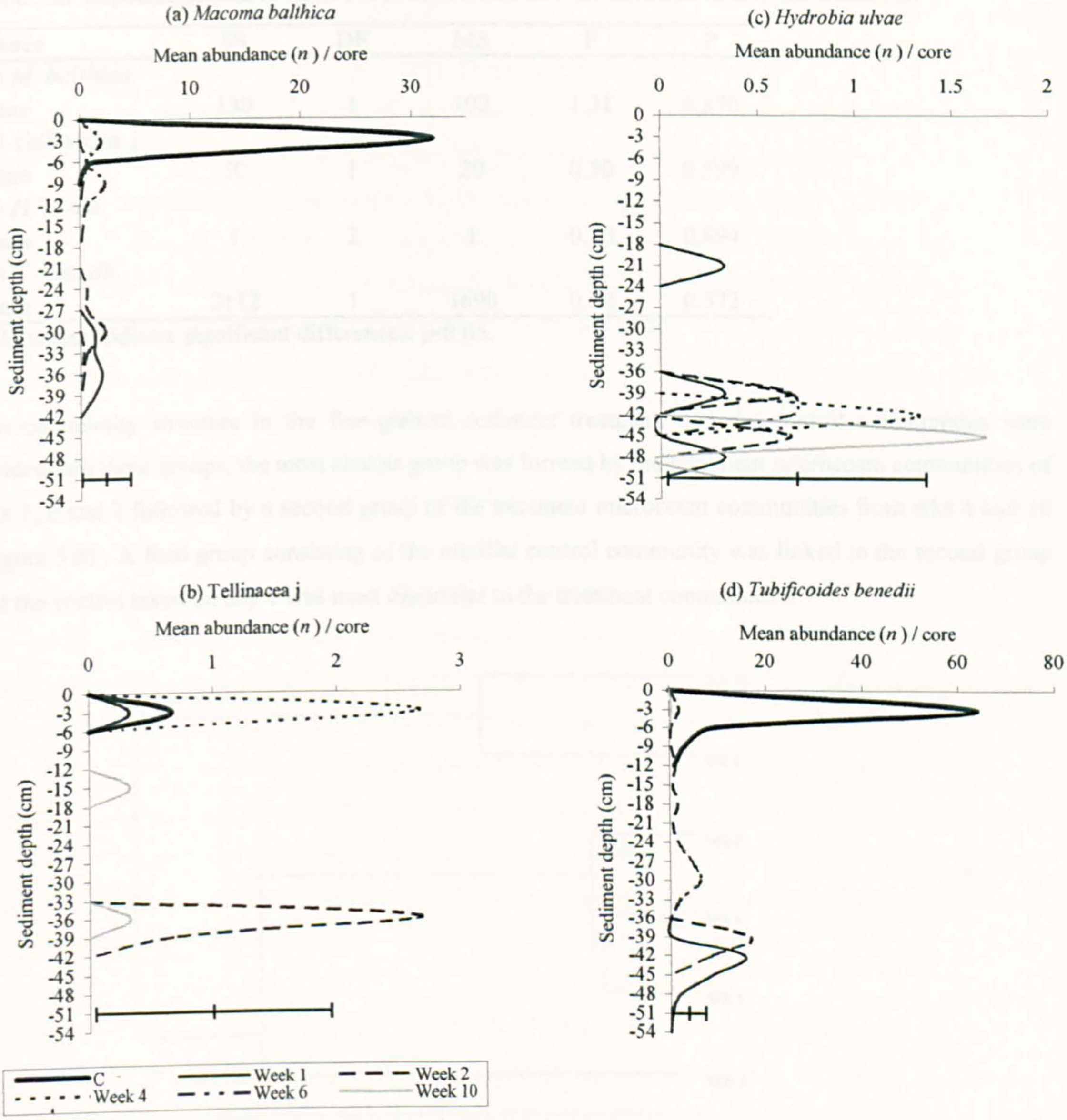


Figure 3.5 (a-d): Mean abundance of common species colonizing the treatment per core per sampling occasion ($n = 3$). Error bars at the bottom of each figure denote (±) pooled Poisson confidence intervals.

The mean abundances of each numerically dominant species in the treatment were not significantly different between times (Table 3.2). Further repeated contrasts revealed a significant difference between time but caution must be used as sphercity may have been compromised when comparing the mean abundance of *M. balthica* in the treatment microcosms of wk 4 with wk 6 and wk 6 with wk 10 (Appendix 2 Table 3.2), an increase of mean abundance from 0 to 19 occurred in the sediment treatment from wks 4 to 6, followed by a decrease to 0 at wk 10 (Figure 3.5 a).

Table 3.2: Repeated measures ANOVA of abundance data for common taxa in the treatment.

Source	SS	DF	MS	F	P
(a) *M. balthica*					
Time	130	1	102	1.31	0.370
(b) *Tellinacea j*					
Time	30	1	20	0.50	0.599
(c) *H. ulvae*					
Time	1	2	1	0.10	0.894
(d) *T. benedii*					
Time	2112	1	1690	0.52	0.572

Bold values indicate significant differences, $p<0.05$.

The community structure in the fine-grained sediment treatment and the control communities were divided into three groups, the most similar group was formed by the treatment microcosm communities of wks 1, 6 and 2 followed by a second group of the treatment microcosm communities from wks 4 and 10 (Figure 3.6). A final group consisting of the mudflat control community was linked to the second group and the control taken on day 1 was most dissimilar to the treatment communities.

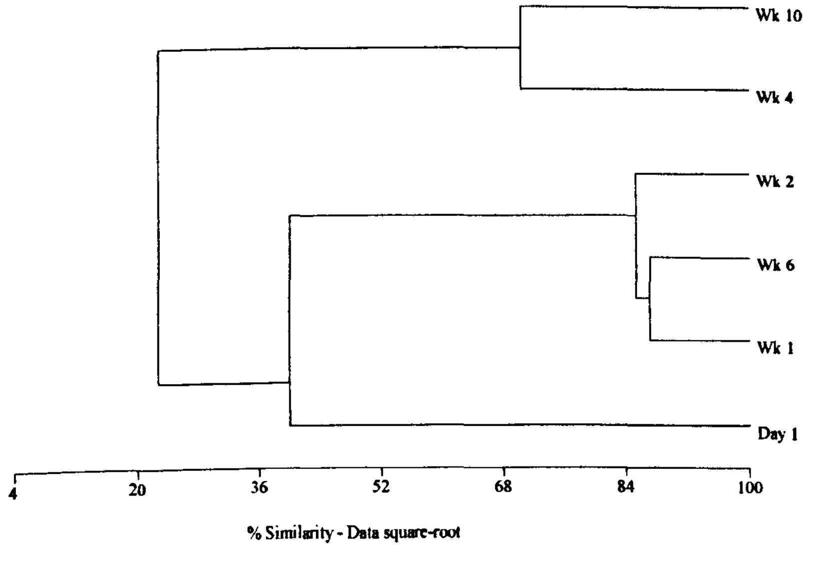


Figure 3.6: Assemblage composition similarity dendrogram of macro-faunal vertical migration into the treatment, average per whole core per sampling occasion.

3.3.2 Macro-faunal horizontal migration

In total 1193 individuals (810 control, 383 treatment) were sampled from 11 taxa (5 control, 11 treatment). Nematodes had the greatest total abundance of 555 individuals however the majority of individuals (552) had colonized the control and few were present in the treatment (3). *Tubificoides benedii* total abundance was 374, with a similar number of individuals present in the control and the treatment of 174 and 200 individuals respectively. *Macoma balthica* had the third highest total abundance of 128 individuals, with 75 individuals sampled from the control and 54 from the treatment. Tellinacea j had a total abundance of 81 however only 3 individuals were sampled from the control and 78 individuals had colonized the treatment. Other species present within the treatment microcosm included *A. tenuis*, *H. ulvae*, *E. longa/flava* agg, *H. diversicolor* and *Paranais litoralis* (O.F. Müller) an oligochaete. Overall the control had the greatest total abundance of individuals (810) sampled on day 1, followed by the treatment microcosm (325) on day 28; day 13 and day 4 had a similar total abundance of 33 and 25 respectively.

The mudflat control had the highest mean abundance of total individuals overall when compared to the treatment microcosm (Figure 3.7 a). However, the mean abundance of total individuals was low during the initial period of the experiment i.e. from day 4 to 13 and the mean abundance later increased by day 28 to 108. The species richness in the treatment microcosm increased over time from 4 to 11 and had exceeded the control species richness of 5 by day 13 (Figure 3.7 b). Overall species diversity increased from day 4 to 28 in the treatment microcosm and the control had a lower diversity when compared to the treatment microcosm (Figure 3.7 c). Pielou's evenness was highest in the treatment microcosm of day 4 and decreased over time (Figure 3.7 d).

The mean abundances of total individuals of the treatment microcosm were significantly different over time (Table 3.3) when comparing a repeated measures analysis of variance between days 13 and 28 (Figure 3.7). However, the mean number of species was not significantly different over time. Further repeated contrasts revealed significant interactions of mean abundance of total individuals between days 13 and 28 (Appendix 2 Table 3.3).

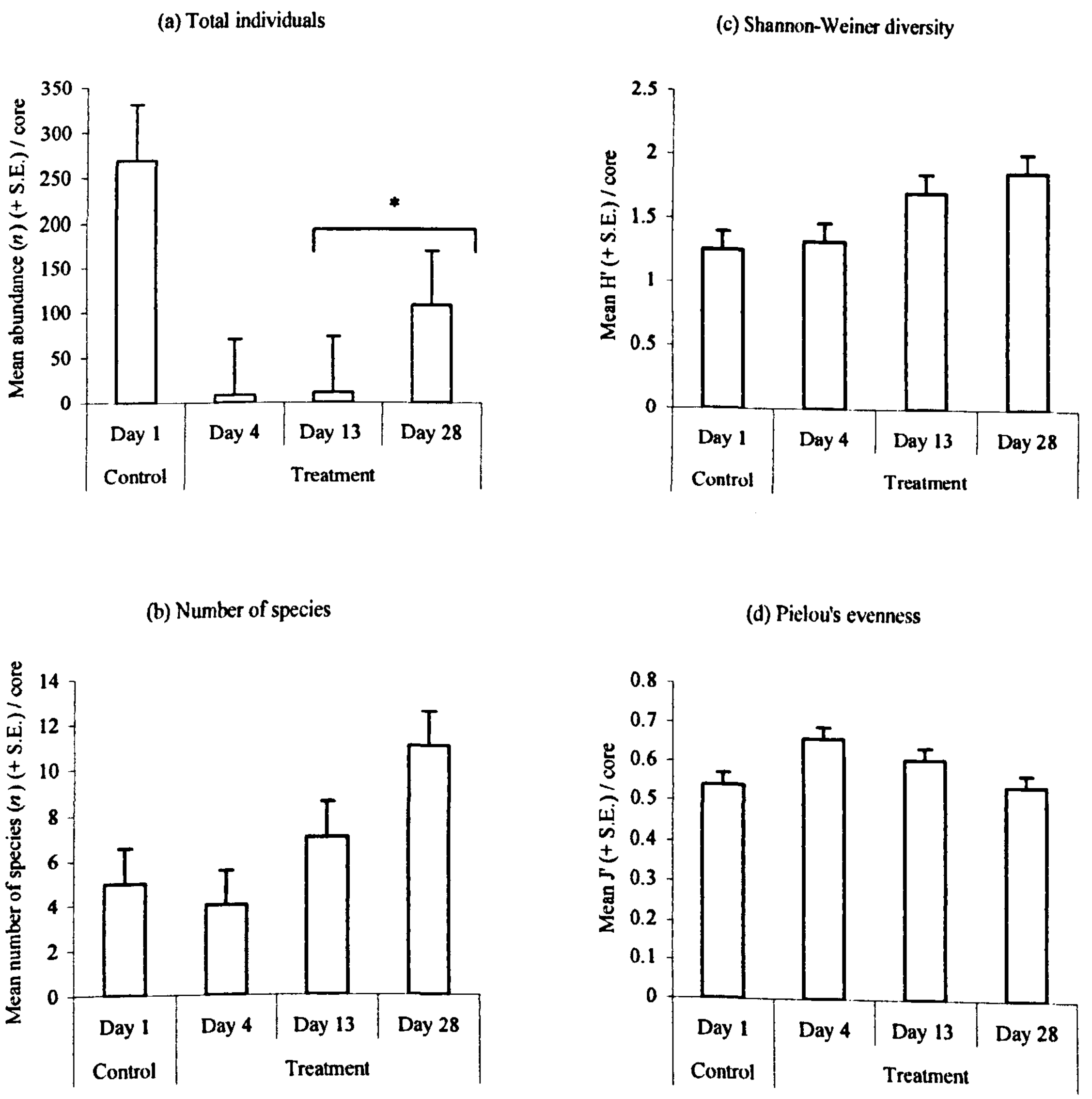


Figure 3.7 (a-d): Univariate indices of macro-fauna in the control and treatment (+ S.E., $n = 3$) per core per sampling occasion. * Denotes significant difference between samples, $p<0.05$.

Table 3.3: Repeated measures ANOVA of univariate indices of macro-fauna in the treatment.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time	**19481**	**2**	**9740**	**23.31**	**0.006**
(b) Number of species					
Time	48	2	24	3.65	0.125

Bold values indicate significant differences, $p<0.05$.

The surface layer of 0-3 cm had the highest mean abundance of 270 total individuals when compared to the deeper mudflat layers in the treatment microcosm of day 4, 13 and 28 (Figure 3.8 a). Some initial colonization of the treatment microcosm occurred but the greatest mean abundance of total individuals in the treatment microcosm occurred at day 28. Some colonization of the treatment microcosm occurred by the horizontal migration of macro-fauna which were distributed throughout the sediment layers of the vertical profile although the highest mean abundance of total individuals was recorded in the surface layer 0-3 cm and decreased with depth on each sampling occasion. The surface layers of 0-3 cm and 3-6 cm contained 99 % of the total individuals present in the control and the cumulative percentage of macro-fauna colonizing the treatment microcosm were distributed throughout the sediment layers (Figure 3.8 b). The treatment microcosm recorded at day 13 had a similar cumulative percentage to the control and the treatment microcosm sampled on days 4 and 28 had a similar cumulative percentage.

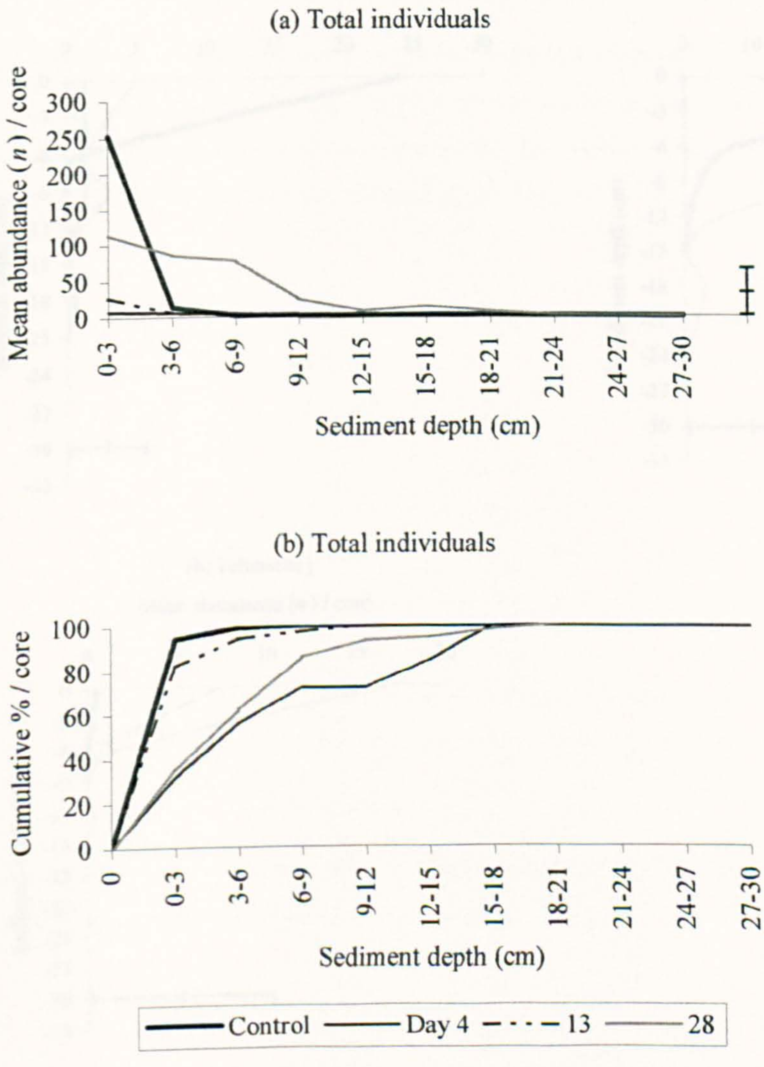


Figure 3.8 (a-b): Mean abundance ($n = 3$) and cumulative percentage of total individuals per layer. Error bars at the bottom of figure (a) denote (±) pooled Poisson confidence intervals.

The control had the highest mean abundance of *M. balthica* in the surface layers of the mudflat of 24 and some individuals had laterally migrated into the sediment treatment at day 4, 13 and 28 (Figure 3.9 a). At day 4 few individuals had laterally migrated to colonize the treatment microcosm and was distributed between layer 0-3 cm and 15-18 cm. By day 13 fewer individuals had colonized the treatment microcosm and some individuals were distributed at layers 3-6 cm and 9-12 cm and more individuals had horizontally colonized the treatment microcosms by day 28 and were distributed between layers 0-3 cm and 15-18 cm. Few Tellinacea j were present in the mudflat control or had colonized the treatment microcosm by day 4, however the presence of Tellinacea j increased over time and was greatest by day 28 (Figure 3.9 b). The surface layer of the mudflat control had the most *T. benedii* individuals when compared to the treatment microcosm (Figure 3.9 c) but few individuals had laterally migrated into the treatment microcosm by day 4 and 13, although they were distributed throughout the treatment microcosm by day 28 and had the highest mean abundance overall when compared to the control.

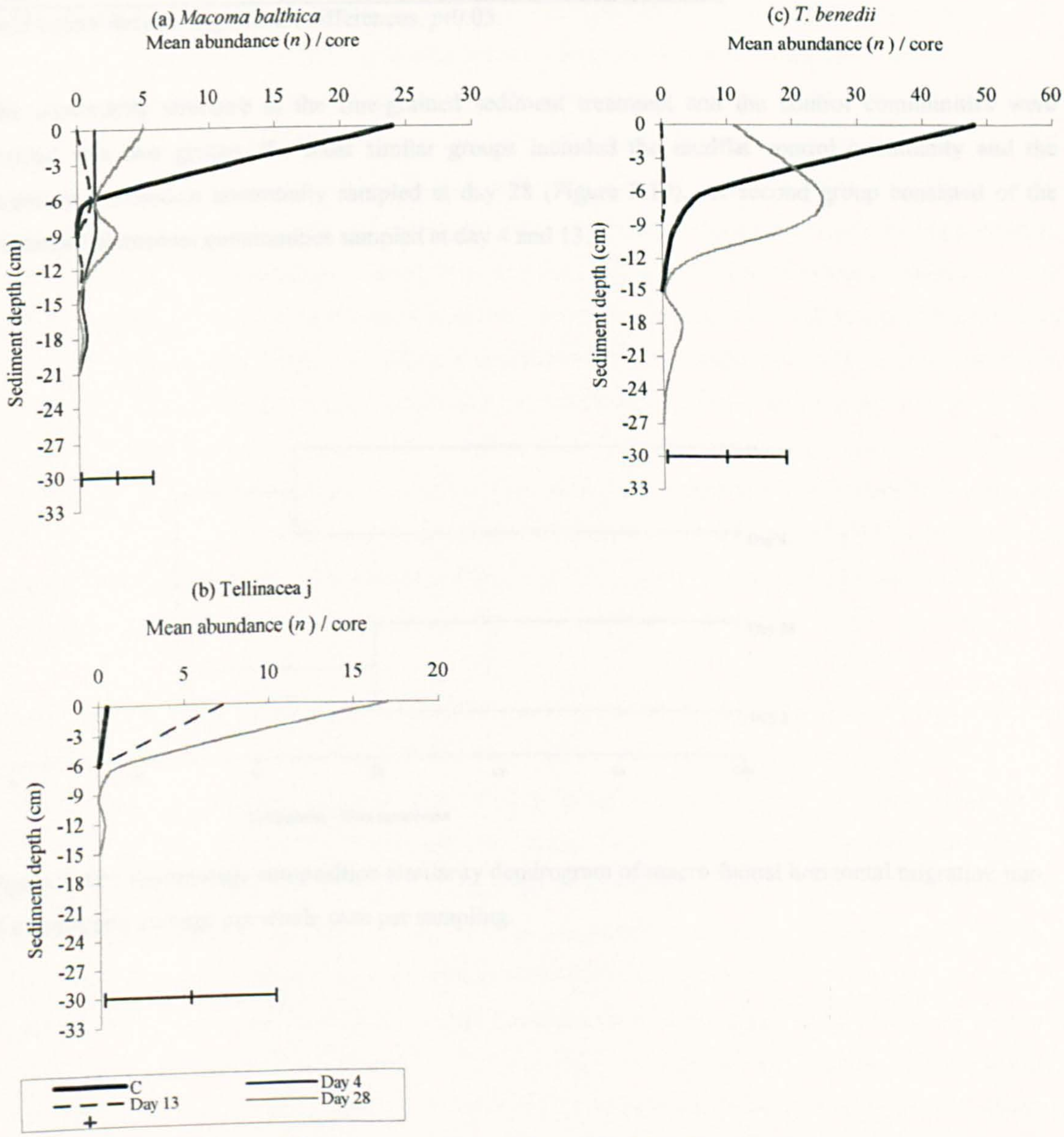


Figure 3.9 (a-c): Mean abundance of common species colonizing the treatment per core per sampling occasion ($n = 3$). Error bars at the bottom of each figure denote (±) pooled Poisson confidence intervals.

The mean abundances of each numerically dominant species such as *M. balthica*, Tellinacea j and *T. benedii* in the treatment were not significantly different between times when comparing a repeated measures analysis of variance (Table 3.4).

Table 3.4: Repeated measures ANOVA of abundance data for common taxa in the treatment.

Source	SS	DF	MS	F	P
(a) *M. balthica*					
Time	131	2	65	3.49	0.133
(b) *Tellinacea* j					
Time	531	2	265	0.56	0.609
(c) *T. benedii*					
Time	8756	1	8755	4.62	0.165

Bold values indicate significant differences, $p<0.05$.

The community structure in the fine-grained sediment treatment and the control communities were divided into two groups, the most similar groups included the mudflat control community and the treatment microcosm community sampled at day 28 (Figure 3.10). A second group consisted of the treatment microcosm communities sampled at day 4 and 13.

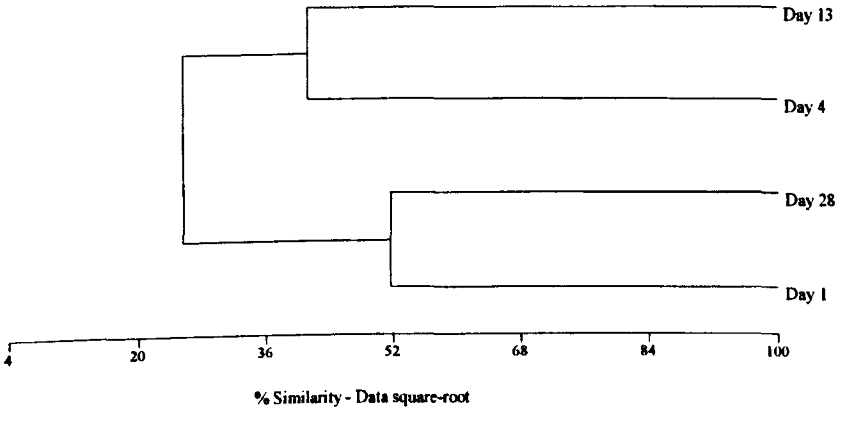


Figure 3.10: Assemblage composition similarity dendrogram of macro-faunal horizontal migration into the treatment, average per whole core per sampling.

3.4 Discussion

The macro-faunal horizontal migration winter period study revealed the recovery of total individuals did not reach the level of the initial situation of the mudflat after 28 days, although an increase of abundance was seen from day 4 to 28. Samples removed on days 13 and 28 showed the species richness recovered quickly and exceeded the initial mudflat situation, with other univariate community indices showing a similar trend indicating species diversity was higher in the treatment than the initial situation of the mudflat. Statistical analysis revealed a significant increase of total individuals horizontally colonizing the treatment from day 13 to 28, therefore, some recovery did occur via the horizontal migration route within the first 28 days post-placement. However, an extended period of study to include the subsequent spring-summer period would highlight the longer-term recovery sequence of benthic macro-fauna. In comparison, Leathem, *et al.*, (1973) monitored the short-term dispersion of maintenance dredged material and macro-invertebrate response at a site behind a breakwater in the Delaware Bay, USA and concluded that the total impact of dredging disposal was small; where initially there was a decrease of univariate parameters such as species richness and diversity following disposal but then a rapid recovery of macro-invertebrates between the winter and summer months. Further comparisons with the actual mudflat community during each sampling occasion of the present study would have shown any changes within a natural assemblage. However, replicate control cores were taken during the initial set-up of the two field experiments and are representative of a natural mudflat benthic community at day 1. A poor short-term recovery of total individuals vertically colonizing the mud treatment occurred from wk 1 to 10 with the abundance of total individuals higher in the initial mudflat situation. However, this study was conducted during the winter period when temperatures are reduced and conditions are less favourable for infaunal migration. In contrast, the initial number of colonizing species was good from wks 1 to 2 and exceeded the species richness in the initial mudflat situation. Similarly, species diversity and evenness in the mud treatment was generally equal to or greater than the initial mudflat situation.

The colonization of the 27 cm depth mud treatment used in this study occurred through the below surface horizontal migration of macro-fauna from the mudflat area adjacent to the microcosm. Rapid colonization of the deposited sediment was probably owing to a ready supply of opportunistic species from the adjacent mudflat. For example, the numerically dominant macro-faunal species that colonized the mud treatment through active horizontal migration was Tellinacea j and *T. benedii*, similarly the latter species was numerically dominant in the vertical migration experiment. However, no significant differences of specific macro-faunal colonization via horizontal migration over time occurred. At day 4, few individuals had actively colonized the mud treatment via horizontal migration. The colonization of the 27 cm depth mud treatment increased by day 13 and 28 and each key species was widely distributed within the sediment treatment profile. In some instances mean abundances were higher in the treatment than the initial mudflat situation, for example, more Tellinacea j colonized the treatment compared to the mudflat on day 1. Indeed community analysis revealed the treatment community of day 28 and the mudflat community on day 1 were the most similar, suggesting some recovery of the treatment macro-benthic community during this period. In addition, the species richness in the mud treatment had recovered by day 28 and exceeded the initial situation on day 1; however, the mean abundance of total individuals was less by day 28. In comparison, a number of scale-dependent defaunation experiments have been carried out to determine the primary macro-faunal re-colonization mechanisms (Thrush, *et al.*, 1996; Levin, 1984). Levin (1984) conducted a series of small-scale defaunation experiments (0.4 m^2 sediment patches) lasting 40 days over a 3 year period, on the Kendall-Frost mudflat at the mid-tide area, Mission Bay, southern California, USA. These resembled biological and anthropogenic disturbances common to the area such as ray foraging activities, bait digging and trampling. She concluded that the total macro-faunal densities did not reach the mudflat control levels in any of the defaunation experiments and that the species richness of experimental plots was similar to the mudflat control following 8 days in year two and 21 days in year three. Additionally, the four common polychaete species *Pseudopolydora paucibranchiata* (Okuda), *S. benedicti*, *Exogone lourei* (Hartman) and *Fabricia limnicola* (Hartman) and Tubificid oligochaetes at the beginning of the experiment, were not significantly different to the species composition at the end of the three year experimental period and the main re-colonization mechanisms were via the horizontal migration from adjacent mudflat areas and from the water column. The errant Syllid *E. lourei* and *Capitella* spp. rapidly colonized the defaunated plots and attainted mudflat control densities within 40 days as did *S. benedicti* during two of the three years. Similarly, Diaz (1994) concluded that recovery of a disturbed area caused by the deposition of fluid mud occurred one month post-placement of mud and that re-colonization was through the adult immigration of opportunistic species from the surrounding areas to the disposal area. However in the present study, the experimental sediment treatment was not fluid and was closer in resemblance to the original mudflat. Furthermore, Flemer, *et al.*, (1997) postulated that the community structure of the disposal area off the coast of Louisiana, USA was not significantly different to the control community and that a relatively rapid recovery occurred at the disposal sites owing to a ready supply of suitable opportunistic colonizers from the adjacent area, for example, the polychaetes *Paraprionospio pinnata* (Ehlers), *Mediomastus californiensis* (Hartman) and *Pseudoeurythoe ambigua* (Fauvel). In contrast, other studies concerning the effects of dredged material deposition on benthic macro-invertebrates have been recorded at open-water disposal sites (Jones, 1986; Harvey, *et al.*, 1998), where minimal detrimental effects on the benthos in a South Carolina estuary occurred (van Dolah, *et al.*, 1984) and an increase in abundance of different taxa was limited to the periphery of a disposal site in the UK (Boyd, 1999). Harvey, *et al.*, (1998) suggested recovery mechanisms such as the larval recruitment of taxa from undisturbed areas and immigration of adults via horizontal migration from undisturbed areas, could explain the gradual re-establishment of a benthic community observed at one and two year old dredged material disposal sites.

More recently, Powilleit, *et al.*, (2006) concluded the re-colonization of dredged material deposited on a shallow sublittoral area of the Mecklenburg Bay (Baltic Sea) was mostly achieved by the active immigration of mobile epifaunal species such as the Cumacean *Diastylis rathkei* (Krøyer) and the ability of some infaunal species to survive burial such as the burrowing of well-adapted species like the deep-burrowing bivalves *Artica islandica* (Linnaeus) and *M. balthica*, enabling a short-term recovery. Indeed both *A. islandica* and *M. balthica* were not significantly affected by the deposition of dredged material but *D. rathkei* and the polychaete *Nephyts hombergii* (Savigny) were slightly affected (Powilleit, *et al.*, 2006). As shown here, few *M. balthica* individuals horizontally migrated to colonize the experimental sediment treatment however juvenile Tellinacea were especially successful horizontal immigrants but crustacean species were absent. Following 28 days of recovery the treatment assemblage had become rich in macro-faunal species, representative of the adjacent mudflat and a short-term recovery was achieved. Powilleit, *et al.*, (2006) in contrast, noted a collapse in a population of taxa more sensitive to burial and characterised by low mobility, examples include the polychaetes *Polydora quadrilobata* (Jacobi), *Pholoe* spp., *Lagis koreni* (Malmgren) and the Tellinid bivalve *Abra alba* (Wood).

During this study, few macro-faunal nematodes (i.e. those individuals retained on a 500 µm mesh size screen) horizontally migrated to colonize the experimental mud treatment following 28 days of recovery, even though nematodes are common in original mudflat assemblages. In contrast, Schratzberger, *et al.*, (2004 b) investigated the horizontal migration of nematodes into mud, sand and mud/sand mixture treatments during laboratory studies over a two-month experimental period. They conclude most nematodes are able to laterally migrate in a sand treatment and re-colonization occurred quickly although over time recovery of the mud treatment became more similar to the control and the meio-faunal community structure of the sand treatment became more dissimilar to the control. In comparison with the present horizontal migration experiment, few macro-faunal nematodes vertically migrated into a single deposition of mud treatment of 50 cm, suggesting nematode species are more sensitive to burial, especially when deposited as a single larger amount. Conversely, Schratzberger, *et al.*, (2000 a & b) found that nematode species were able to vertically migrate into muddy and sand sediment deposited in different amounts and frequencies and recovery of a meio-faunal mudflat assemblage of nematodes, in sand treatment occurred throughout an experimental period of two-months. However, the depth of sediment deposition (6 cm) was much less than the present study and concluded a single deposition of treatment was found to be more detrimental to the meio-faunal assemblage when compared to smaller multiple depositions.

Difficulties are experienced when comparing migratory abilities of species between studies as migration is affected by several variables such as sediment type; deposition depth, frequency of deposition, tidal height and taxonomic differences. For example, Kranz (1972, in Hall, 1994) studied the burrowing ability of 30 species and concluded that species of certain feeding guilds, for example, mucous-feeders and suspension-feeders were more susceptible to a sediment overburden, whereas, an increase of burial depth for some groups, for example, infaunal non-siphonate suspension-feeders, were able to withstand a 5 cm sediment overburden and a 50 cm overburden is survivable by deep-burrowing siphonate suspension-feeders. As shown here, following 2 wks post-placement, recovery continued to increase and species such as *M. balthica* and Tellinacea j had migrated vertically to reach the surface layers of a 50 cm fine-grained sediment treatment, although abundances were low. The present *in situ* research supports the findings of Kranz (1972, in Hall, 1994), for example, when a single placement of mud treatment to a depth of 50 cm was added, re-colonization of the deposited sediment began to take place after 1 wk of burial with a few Tellinacea j vertically migrating through 50 cm to reach the surface layer.

Onshore recharge is generally used to achieve a quick result in terms of required elevation changes to a recharge area and its profile. The protection of an eroding area can be obtained relatively quickly. However, the direct placement of increased amounts of dredged material onto the mudflat may have a detrimental impact on the estuarine benthos. Indeed, Essink (1999) suggests a causal relationship exists between the survival rates of mobile benthic fauna and the depth a sediment deposition veneer is placed. As shown here, both *M. balthica* and *T. benedii* were able to survive burial of a large deposition of fine-grained sediment treatment to a depth of 50 cm and vertically migrate to the surface layers following 6 weeks post-placement, however macro-faunal nematodes exhibited a poor colonization ability and crustacean species were absent (Table 3.5). Similarly, Van Dolah, *et al.*, (1984) investigated the recovery of benthic invertebrates following the placement of a large amount of fine-grained dredged material in the North Edisto River, an estuary in South Carolina, USA and noted initially macro-benthic recovery was slow. However, three months post-disposal the community began to recover and the benthic community was compared to a control reference site from an unimpacted area. The original macro-zoobenthic community of the disposal area was dominated by two mobile crustacean species, the amphipod *Ampelisca vasorum* and the Caprellid *Caprella equilibra* (Say). However, the dredged material was colonized by those species present prior to disposal and included *A. vasorum*, *C. equilibra*, the Spionid polychaete *S. benedicti* (Webster) and the amphipod *Lembos websteri* (Bate). Following six months post-disposal the macro-zoobenthic community was similar to the reference site.

Table 3.5: Summary of the ability of mudflat macro-fauna to vertically migrate through a fine-grained sediment deposition of 50 cm.

Species	Week 1	Week 2	Week 4	Week 6	Week 10
Macoma balthica	23 cm	47 cm		50 cm	
Tellinacea juveniles	50 cm	50 cm	50 cm		
Hydrobia ulvae	33 cm				
Tubificoides benedii	14 cm	14 cm		50 cm	50 cm

Note: these findings are based on the assumption that the influx of macro-fauna through the mesh was excluded and that no damage or loose mesh-fittings were detected.

The surface layers of the initial situation of the mudflat had the highest mean abundance of *M. balthica* when compared to the re-colonization of the sediment treatment over the experimental period. At wk 1 a few individuals had vertically migrated through at least 23 cm to reach the treatment layer 27-30 cm. In comparison, some individuals had vertically migrated to reach the surface layers of the sediment treatment by wks 2 and 6 after vertically migrating through at least 47 cm and 50 cm of sediment overburden respectively. Similarly, by wks 1, 2 and 4, a few Tellinacea j had reached the treatment surface by vertically migrating through at least 50 cm of sediment treatment. In the present study, *H. diversicolor* individuals were recorded within the sediment profile of the mud treatment following vertical migration from the original mudflat core, although numbers were too low for statistical analysis. In comparison, de Deckere, *et al.*, (2001) investigated the ability of key mudflat macro-fauna to re-colonize manipulated sediment and concluded that *H. diversicolor* was able to migrate to the surface and surrounding areas of defaunated intertidal experimental plots but less motile infauna such as *M. balthica* and *S. shrubsolii* were less able to do so.

Hydrobia ulvae individuals colonized the mud treatment of 50 cm depth in the present study and had migrated through 33 cm of sediment overburden by wk 1 although re-colonization of the upper sediment layers did not occur. This contrasts with the findings of Bolam (2003) who noted the vertical distribution of *H. ulvae* and *S. shrubsolii* in the sediment treatments were restricted to the top 2 cm. In the present vertical migration study *T. benedii* initial colonization was restricted to the deeper layers of the sediment treatment after vertically migrating through a minimum of 14 cm of sediment overburden. However, over a prolonged period of recovery, *T. benedii* exhibited a good migratory ability and colonization of the surface layers of the mud treatment occurred at wks 6 and 10 after vertically migrating through 50 cm of sediment overburden, additionally at wk 6 individuals were evenly distributed between layers 0-33 cm and supports the findings of Bolam (2003) where the vertical distribution of *T. benedii* in the sediment treatments were widespread and most abundant at the surface.

Therefore, a range of mudflat macro-fauna vertically migrated into the 50 cm mud treatment, although certain species were quicker and more able to migrate vertically through the sediment profile whilst others appeared to migrate slowly to the surface layers (Table 3.5). The numerically dominant colonizing species of this study was *T. benedii.* The subsequent chapter further investigates the frequency and amount of fine-grained sediment deposition; changes to the sedimentary characteristics of experimental treatments and the ability of mudflat species to colonize a sediment overburden via immigration from above.

3.5 Conclusions

- The short-term recovery of total individuals horizontally migrating into the mud treatment had significantly begun to increase following 28 days but did not exceed the initial mudflat total abundance. In contrast, the number of species that horizontally migrated into the treatment following 13 and 28 days exceeded the number present in the initial mudflat situation. Similarly, species diversity and evenness in the mud treatment from day 4 to 28 was equal to or exceeded the initial mudflat situation.
- A poor short-term recovery occurred of total individuals vertical migration into the mud treatment. In contrast, the initial number of colonizing species was good from wks 1 to 2 and exceeded the species richness in the initial mudflat situation. Similarly, species diversity and evenness in the mud treatment was generally equal to or greater than the initial mudflat situation. However, this study was conducted during the winter period when temperatures were reduced and conditions less favourable for infaunal migration.
- A single placement of mud treatment to a depth of 50 cm produced re-colonization of the deposited sediment following 1 wk of burial; for example, a low number of Tellinacea j had vertically migrated through 50 cm to reach the surface layer. After 2 wks post-placement *M. balthica* individuals had reached the surface layers of a 50 cm sediment overburden whilst *T. benedii* individuals had vertically migrated through 14 cm of sediment overburden. After 6 wks of burial *T. benedii* individuals were present in the upper layers of the sediment overburden. It is concluded that *M. balthica*, Tellinacea j and *T. benedii* exhibited some ability to vertically migrate throughout a fine-grained sediment overburden of 50 cm.
- The re-colonization of sediment treatments via the below surface horizontal migration of macro-fauna occurred when 27 cm of fine-grained sediment treatment was added. Again the main macro-faunal colonizers were *M. balthica*, Tellinacea j and *T. benedii* exhibiting some ability to horizontally immigrate into deposited mud treatment.
- *T. benedii* was the numerically dominant colonizing species of this study.
- The deposition of a single large amount of fine-grained sediment had a detrimental affect on macro-faunal nematode re-colonization.
- The ability of common estuarine benthic species to re-colonize larger amounts of deposited fine-grained sediments through the vertical and horizontal migration into simulated dredged material was tested in the field and further testing of the concept of re-colonization of deposited sediments was also investigated in field experiments.

4 Macro-faunal re-colonization of simulated dredged material via settlement

4.1 Introduction

The total impact of dredgings disposal on benthic invertebrates is dependent on many factors; the scale of an impact can vary. For example, Leathem, *et al.*, (1973) observed a decline in biological and environmental parameters such as dissolved oxygen and animal density whilst Jones (1986) noted a reduction in species richness but a high abundance of total individuals as a consequence of surviving burial. Therefore, the physical, chemical and biological parameters of the dredged material such as the re-colonization potential, consolidation, particle size, consistency and contamination levels, indicate the most suitable use of fine-grained material. A number of criteria are used to determine whether a beneficial use scheme is granted a licence to take place and include, the amount and frequency of dredged material deposition, the physio-chemical and sedimentary characteristics of dredged material and the similarity and nature of the receiving environment. Previous work, however, has not determined the influence of the amount and frequency of sediment deposition in determining the extent to which the biotic recovery processes of the receiving intertidal area may become adversely affected following recharge (Harvey, *et al.*, 1998; Elliott, *et al.*, 2000). The resulting nature of an intertidal benthic community may change greatly as an individual species' burial tolerance and burrowing ability differs with increased sediment depths (Elliott, *et al.*, 2000). However, specific species may be better adapted to stress and recover quickly from frequent or single episodes of burial (Jones, 1986; Minello, 2000). Despite this, there are few indications in the literature of the response of individual species under particular recharge scenarios.

There are three successive phases to re-colonization, but it is the reproductive strategies of benthic macro-invertebrates that ultimately facilitate the recruitment pattern seen in soft sediment habitats. These strategies are dependent on inter-annual variation and the strength of the prevailing current, both influence particular life stages of each species, which includes the swarming and settlement period, larval development and the growth strategy. Rasmussen (1973) concluded that the timing of larval release of common estuarine invertebrates coincided with a spring-summer swarming period (Figure 4.1) however the data are for Denmark but are not dissimilar from the Humber. The settlement of benthic invertebrates is an important recovery mechanism of newly deposited sediments. The densities of most tidal flat benthic macro-fauna naturally change according to the season and the recruitment period of spring and early summer exceeds mortality, whereas during the autumn period the mortality rate increases, such events may occur differently within a dredged material recharge area when compared to the surrounding mudflat area. Beukema, *et al.*, (1999) noted high densities of macro-fauna within defaunated sediment plots by the late summer when compared to the surrounding mudflat area but no differences of mortality during autumn between areas. Therefore, winter sediment recharge depositions would be re-colonized rapidly as placement occurred prior to the main larval recruitment phase, on the other hand, summer recharge depositions may smother benthic recruits (Elliott, *et al.*, 2000) and re-colonization would not occur until larval recruitment the following year. This was demonstrated by the deposition of fine-grained maintenance dredged material used at a beneficial use scheme at the Westwick Marina, along the Crouch Estuary, UK which was completed in August 2001. The evidence pointed towards the post-juvenile immigration of macro-fauna as the main recovery mechanism, following 18 months of monitoring (Bolam and Whomersley, 2003).

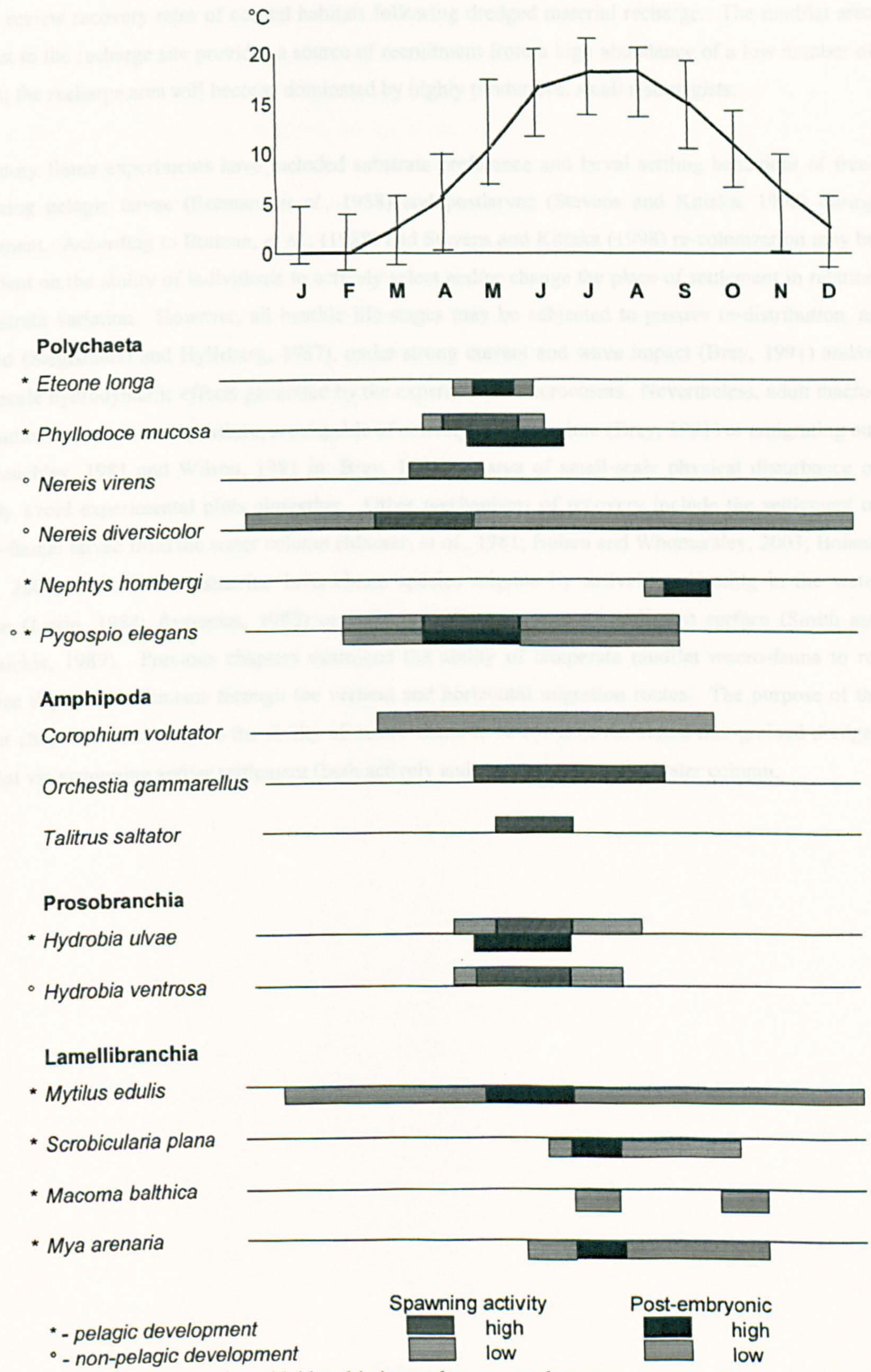


Figure 4.1: Selected common intertidal benthic invertebrates – settlement over a year (Rasmussen, 1973).

The mudflat areas requiring recharge are often located within a shallow estuarine habitat and are naturally dominated by an opportunist species composition (stage I taxa) such as oligochaetes and nematodes. Such environments are regarded as stressed and often remain in a stage I phase of recovery, lacking a successional sequence following a disturbance event from dredged material deposition, Bolam and Rees (2003) review recovery rates of coastal habitats following dredged material recharge. The mudflat area adjacent to the recharge site provides a source of recruitment from a high abundance of a low number of species; the recharge area will become dominated by highly productive, small r-strategists.

Laboratory flume experiments have included substrata preference and larval settling behaviour of free-swimming pelagic larvae (Butman, *et al.*, 1988) and postlarvae (Stevens and Kittaka, 1998) during recruitment. According to Butman, *et al.*, (1988) and Stevens and Kittaka (1998) re-colonization may be dependent on the ability of individuals to actively select and/or change the place of settlement in relation to substrata variation. However, all benthic life-stages may be subjected to passive re-distribution, as bedload (Siegismund and Hylleberg, 1987), under strong current and wave impact (Brey, 1991) and/or small-scale hydrodynamic effects generated by the experimental microcosms. Nevertheless, adult macro-zoobenthos that are errant by nature, are capable of actively migrating into (Brey, 1991) or emigrating out of (Brenchley, 1981 and Wilson, 1981 in: Brey, 1991) an area of small-scale physical disturbance or actively avoid experimental plots altogether. Other mechanisms of recovery include the settlement of macro-faunal larvae from the water column (Maurer, *et al.*, 1981; Bolam and Whomersley, 2003; Bolam, *et al.*, 2004) whilst some estuarine invertebrate species migrate by actively swimming in the water column (Levin, 1984; Armonies, 1988) or actively emigrate across the sediment surface (Smith and Brumsickle, 1989). Previous chapters examined the ability of temperate mudflat macro-fauna to re-colonize deposited sediments through the vertical and horizontal migration routes. The purpose of the present chapter is to determine the ability of macro-fauna to re-colonize simulated fine-grained dredged material via swimming and/or settlement (both actively and passively) from the water column.

4.1.1 Aims, objectives and null hypotheses

This manipulative field experiment was aimed at improving our ability to predict the affects of changes in water content on macro-faunal re-colonization of simulated dredged material through settlement from the water column at different tidal heights of an intertidal mudflat (including the upper-, high- and mid-shore). It was important to include the settlement of both adult and juvenile macro-fauna in the study therefore the experimental set-up was designed to take into account the seasonal macro-faunal recruitment phase in the spring. The main objectives of the study were to compare (a) univariate community characteristics and (b) species composition of different tidal heights and to determine if changes to the water content of a manipulated sediment treatment influences biotic re-colonization. In particular, the following null hypotheses were tested: (1) macro-faunal re-colonization is not affected by changes in water content of simulated dredged material and (2) macro-faunal re-colonization is not affected by the amount of treatment deposition, (3) macro-faunal re-colonization of simulated dredged material is not affected by tidal height. This information may be used during the decision making process upon the feasibility of the alternative beneficial uses of dredged material such as when determining the type of dredged material used during a sediment recharge scheme or during simulated dredged material deposition studies.

4.1.2 Study experimental site

The experimental site was located at the Skeffling mudflats, along the Humber Estuary, as described previously in chapter one.

4.2 Methods and Materials

An investigation into the invertebrate re-colonization of simulated dredged material through macro-faunal recruitment at three tidal heights the upper-, high- and mid-shores, along two transects was implemented in April 2002. In order to examine the effects of sediment water content variation and macro-faunal settlement a manipulated fine-grained sediment treatment was used. To collect the simulated fine-grained dredged material (approx. 45 x 5 l containers) the top 4 cm surface layers of an area of mudflat was extracted from the high- to mid-shore of the Skeffling mudflats. The sediment was later defaunated using a freeze-thaw method described previously.

4.2.1 Treatment and control descriptions

The surface water was decanted from each 5 l container following defaunation and prior to water content manipulation. The treatment contained a mix of 500 ml of filtered seawater (29) added to 5 l of native defaunated mud to obtain an overall mean water content of 40 % (see sediment analysis) and a mean wet bulk density of 0.95 g cm $^{-3}$. Bulk density was calculated using the method (mass wet sediment/volume of wet sediment) described by Widdows, *et al.*, (2000, 2006). To test the homogeneity of the material, a number of 50 ml sub-samples were randomly removed for further sediment analysis. Following the freeze-thaw process, the defaunated mud used for the control 1 was homogenized and the mean water content of 34 % and the mean wet weight bulk density of 0.88 g cm $^{-3}$ remained un-manipulated. Similarly, the natural mudflat sediment cores had a mean water content of 33 % and a mean wet weight bulk density of 1.04 g cm $^{-3}$. In order to examine both the rate and the frequency, 170 ml depositions of the sediment treatment and control 1 were transferred into 200 ml sealed plastic containers and stored in a freezer at –20 °C. The total volume of material added to gain the required simulation depth per microcosm was calculated, for example, the deposition volume for a simulation depth of 15 cm (v/ 7 depositions) was 1190 ml and each deposition depth (1190 ml / 7) was 170 ml.

Transect one experimental sites were located at the upper-shore (53 °N 38.577, 000 °E 04.073) (Plate 4.1) and high-shore (53 °N 38.528, 000 °E 04.021) (Plate 4.2) whereas transect two had experimental sites at the high-shore (53 °N 38.503, 000 °E 04.076) (Plate 4.3) and mid-shore areas. At each experimental site, a total of 42 Perspex tubes (10.4 cm id x 35 cm d) including 21 treatment and defaunated control microcosms were placed within a randomised grid block design (1 m^2) (Figure 4.1) to a depth of 15 cm. A total of three experimental blocks were set-up at each tidal height, each containing a labelled microcosm replicate of treatment (T1) and a replicate of defaunated control (C1). Using a core sampler (10.4 cm id x 20 cm d) a second control (C2) was taken from an undisturbed area of the established mudflat, next to each experimental site, this also provided an indication of the nature of the estuarine benthos.


Plate 4.1: Upper-shore transect 1, 2002. (The arrow points to the study area).


Plate 4.2: High-shore transect 1, 2002. (The arrow points to the study area).


Plate 4.3: High-shore transect 2, 2002.

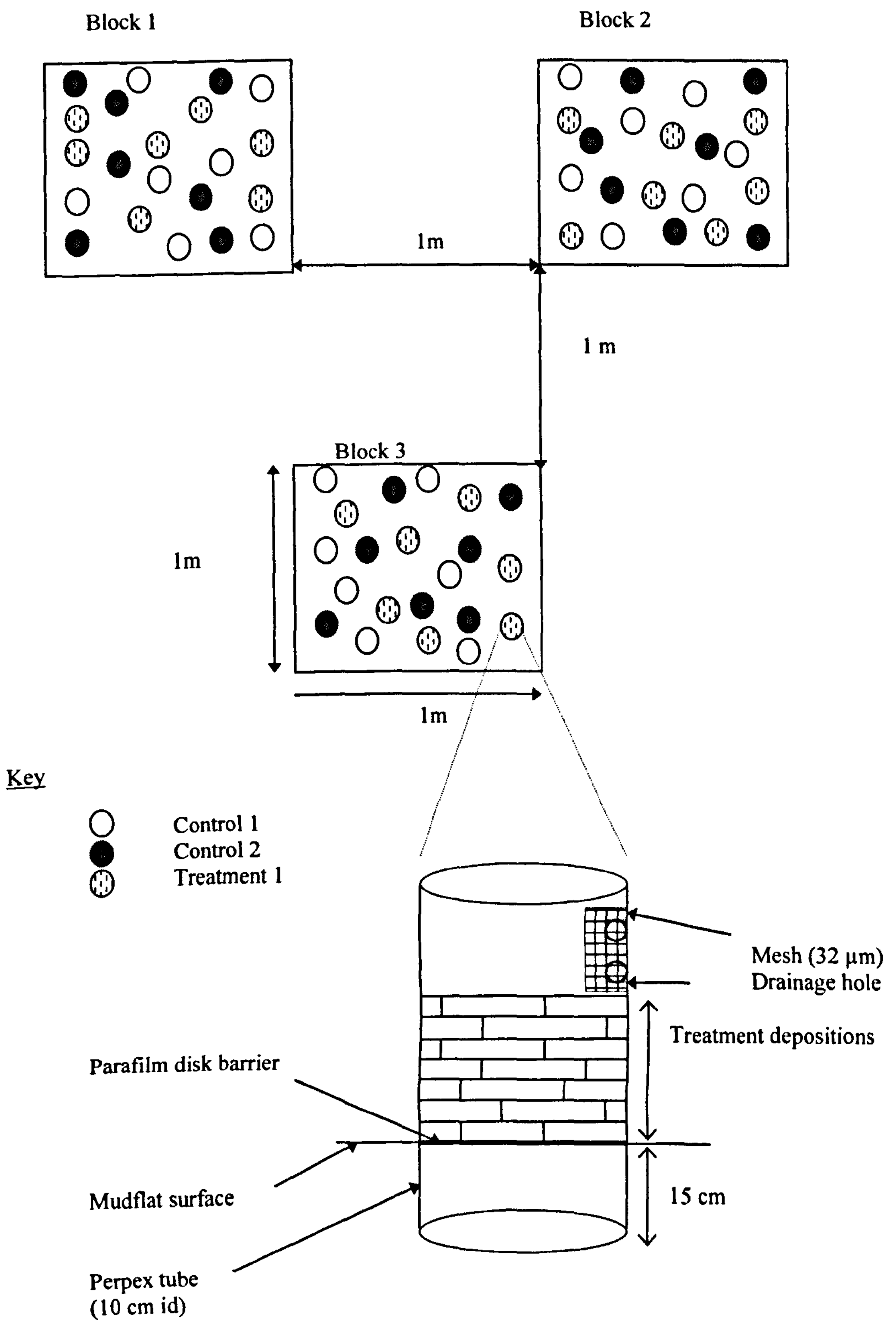


Figure 4.2: Experimental set-up of plot types and core positions ($n = 3$).

Prior to treatment placement, a number of drainage holes had been drilled into each tube. Each drainage hole was positioned above the simulated dredged material surface, to prevent any standing water occurring (Figure 4.2) (Plate 4.4). A circular section of Parafilm (10.4 cm id) was placed inside each tube to separate the surface mudflat from the simulated dredged material deposition. This method would act as a faunal barrier thus preventing migration or escape via the sides or the base, directing any movement into the area from the route above.

Plate 4.4: Microcosm drainage holes & treatment deposition layers.

Two days prior to each sediment deposition occasion, the required amount of treatment and control 1 sub-samples were removed and left to thaw at ambient room temperature (20 °C). Each 170 ml sub-sample was later homogenized a second time as the freezing process alters the sediment structure. At the field site the sub-samples (T1 and C1) were placed into the centre of each microcosm (Plate 4.5).

Plate 4.5: Treatment deposition within a microcosm. (The arrow points to the sediment treatment).

4.2.2 Treatment and control depositions and sample removal

Thereafter on each sediment deposition occasion, three replicates of control 1, control 2 and treatment 1 were extracted and immediately sectioned into 2 cm increments, thus allowing any macro-fauna settlement to be examined. All 2 cm veneers were preserved *in situ* during each sampling occasion with 4% formo-saline solution with Rose Bengal stain to aid extraction of the fauna. A 170 ml treatment 1 or control 1 was added to the remaining microcosms, over a total of seven deposition periods (Figure 4.3). To simulate the conditions during the operational aspect of a recharge scheme, in particular the trickle method of dispersion, the deposition of simulated dredged material over time and placement to different depths was implemented at the upper- and high-shore areas transect 1 (Table 4.1) and at the high- and mid-shore transect 2 (Table 4.2). The timing of sediment depositions was arranged around the macro-faunal recruitment phase to include before, during and after.

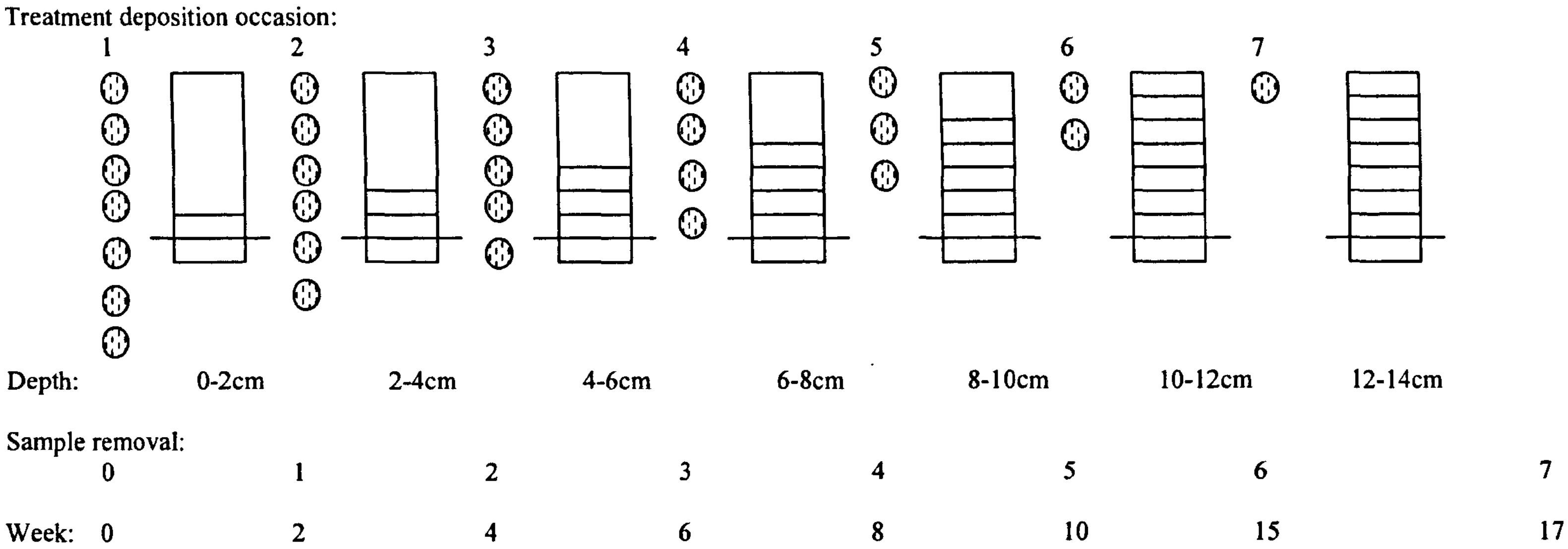


Figure 4.3: Experimental set-up of the treatment depositions and sample removal per experimental blocks of the upper- and the high-shore transect 1 (n = 3).

Table 4.1: Upper- and high-shore treatment deposition & sampling occasions transect 1, 2002.

Sampling date	Treatment & Controls	Placement No.	Deposition (ml)	Sampling occasion	Sampling week
07/05/02	T1 & C1	1	170	0	0
	C2	0		1.1	
21/05/02	T1 & C1	2	340	1	2
	C2	0		1.2	
05/06/02	T1 & C1	3	510	2	4
	C2	0		2	
18/06/02	T1 & C1	4	680	3	6
	C2	0		3	
02/07/02	T1 & C1	5	850	4	8
	C2	0		4	
16/07/02	T1 & C1	6	1020	5	10
	C2	0		5	
20/08/02	T1 & C1	7	1190	6	15
	C2	0		6	
03/09/02	T1 & C1	0		7	17
	C2	0		7	

Table 4.2: High- and mid-shore treatment deposition & sampling occasions transect 2, 2002.

Sampling date	Treatments & Controls	Placement No.	Deposition (ml)	Sample occasion	Sampling week
15/04/02	T1 & C1	1	170	0	0
	C2	0		1.1	
29/04/02	T1 & C1	2	340	1	2
	C2	0		1.2	
13/05/02	T1 & C1	3	510	2	4
	C2	0		2	
27/05/02	T1 & C1	4	680	3	6
	C2	0		3	
13/06/02	T1 & C1	5	850	4	8
	C2	0		4	
24/06/02	T1 & C1	6	1020	5	10
	C2	0		5	
08/07/02	T1 & C1	7	1190	6	12
	C2	0		6	
22/07/02	T1 & C1	0		7	14
	C2	0		7	

4.2.3 Faunal analysis

All samples were left for at least 48 h, to allow staining to take place, each sample was then passed through two sieves of a 500 µm and a 125 µm mesh screen, thus separating juveniles from adult macro-fauna and any larger meio-faunal specimens, and simplifying extraction. The macro-faunal recruits retained on the 125 µm mesh were stored in 4 % formo-saline buffered solution with Rose Bengal vital stain for further analysis. All adult macro-fauna retained on the 500 µm were sorted using a stereo dissecting microscope and placed into taxonomic groups and stored in 70% IMS and labelled with the sampling occasion, treatment type, replicate and increment number. Identification and enumeration of all specimens was carried out.

Biological tissue can be estimated as wet weight biomass, dry weight and ash free dry weight (AFDW) whereas the first of these reflects material taken by predators; the last is a standard measure of organic matter. The biota of the upper-shore transect 1 and the high- and mid-shores transect 2 were weighed to achieve a wet weight biomass. Each group was washed with distilled water then blotted dry. The balance was allowed to zero and each group was weighed after 30 seconds. To achieve an dry weight biomass each group was placed into separate porcelain dishes and dried at 86 °C until constant weight was attained (48 h). Each dried sample was placed in a desiccator and allowed to cool. The samples were weighed as described above. Lastly, an ash free dry weight was reached by placing each sample into the muffle furnace for 4 h at 475 °C. The samples were left to cool in a desiccator and later weighed. The final weight was subtracted from the ash dry weight sample to give ash free dry weight as described by Hartley, *et al.*, (1987).

4.2.4 Sediment analysis

Several environmental parameters were measured in order to determine any correlation between these and the biota and between tidal heights. Sub-samples of the controls and treatment sediments were analysed in a Malvern Mastersizer 2000 for particle size distribution to give descriptive statistics such as the median and mean particle grain size, percentage sand and silt/clay fractions, skewness and kurtosis. Additionally other sediment parameters such as percentage dry weight, the carbon content expressed as the percentage loss on ignition (L.O.I.) and percentage water content were determined. The sediment samples were placed in a deep freeze upon return to the laboratory. This was necessary in order to prevent the mineralising effects of microorganisms upon the organic matter present in the sediment and therefore produced data that are more accurate. A 2.5 g sediment sub-sample was weighed once the balance had returned to zero. Each sub-sample was dried for 24 h at 86 °C and later weighed following cooling and recorded as dry weight. Each sediment sub-sample was placed in a muffle furnace for 4 h at 474 °C. Ash free dry weight was calculated as described earlier and the value for percentage loss on ignition (L.O.I.) was produced. The percentage water content was determined as the wet weight subtracted from the dry weight.

4.2.5 Data analyses

The invertebrate data were analysed using both univariate and multivariate techniques. The data were checked for normality using the Kolomogrov-Smirnov test and homogeneity of variances were tested using a Levene's test and descriptive statistics were determined. Any data not conforming to a normal distribution were transformed using a square-root transformation (Zar, 1996). As the same plots were sampled throughout the experiment, there was an increased risk of a type I error being committed resulting in the possibility of non-independence occurring during sampling times. To test the effect of treatment and time on community variables and species abundances, repeated measures analysis of variance tests were performed in which treatment and time were within effect factors and tidal height was considered a between effect factor. If Mauchly test of spherecity was violated then a Greenhouse-Geisser correction factor was applied to that factor during a within effects repeated measures analysis of variance (Field, 2000). Additionally, the data were tested for homogeneity of variances using a Levene's test. A repeated contrast of between effects was conducted to determine which factor differed to another at each time and treatment at each tidal height. Bonferroni multiple comparison tests were performed to investigate any differences between time and between treatments. All univariate analyses were conducted using SPSS version 13.

The Shannon-Wiener index was used to indicate community diversity. This was estimated by integrating species richness and relative abundance (Barker, *et al.*, 1987). Pielou's evenness was conducted using MVSP version 3.12a. Multivariate analyses were performed on species abundance data to assess (dis) similarities between community assemblages between treatments at each sampling time. Classification analysis (group-average linking from the similarity matrix) was conducted on the data of all treatments and controls on all sampling occasions. A dendrogram was used to illustrate the relative importance of time and treatment on community changes at each tidal height. All multivariate analyses were performed using MVSP version 3.12a. A Spearman Rank bivariate correlation test was used to determine any links between species abundance and community variables and sediment variables. Principal Components Analysis (PCA) was performed on the sediment variables. Canonical Correspondence Analysis (CCA) a multivariate correlation test was used to determine any relationships between faunal colonization and measured sediment variables, such as percentage water content and percentage silt/clay content. The ordination diagram showed links between individual species and sediment variables.

4.3 Results

4.3.1 Sediment variables transects 1 and 2, 2002

4.3.1.1 Upper-shore transect 1

The percentage water content was successfully manipulated to produce a sediment treatment with high water content (40.0 %). The defaunated control 1 had similar mean percentage water content to the mudflat control of the upper-shore of 34.0 and 33.0 % respectively (Figure 4.4 a). The mean percentage silt/clay content was high in general and similar throughout control 1, control 2 and treatment with 89.0, 90.0 and 88.0 % respectively (Figure 4.4 b). The mean percentage dry weight was similar in the controls with 55.0 and 56.0 % respectively and treatment 1 (48.0 %) was markedly lower when compared to the controls (Figure 4.4 c). In general the mean percentage loss on ignition (L.O.I.) was lower in the treatment (3.5 %) than control 1 (3.7 %) and control 2 (3.8 %) and was less than the controls on each sampling occasion (Figure 4.4 d).

4.3.1.2 High-shore transect 1

The water content of the treatment (40.0 %) was greater than the controls (34.0 %) (Figure 4.5 a). The mean percentage silt/clay content was generally similar in the controls and the treatment (Figure 4.5 b). Treatment 1 had a lower mean dry weight of 48.0 % when compared to the controls (56.0 % respectively) (Figure 4.5 c). Percentage L.O.I. was greater in the controls when compared to the treatment on each sampling occasion and was highest in control 2 (3.9 %), followed by control 1 (3.8 %) and the treatment (3.5 %) (Figure 4.5 d). Overall the sediment variables were similar in the upper- & high-shore experimental blocks.

4.3.1.3 Mid-shore transect 2

Treatment 1 had a water content of 40 % and the controls had a similar water content on each sampling occasion, (34.0 %) (Figure 4.6 a). The mean percentage silt/clay content of 90.0 % was generally high and similar throughout the controls and treatment (Figure 4.6 b). Percentage dry weight was similar between the controls but less in the treatment on each sampling occasion (Figure 4.6 c). The mean percentage L.O.I. was higher in the controls (3.9 %) when compared to the treatment (3.5 %) (Figure 4.6 d).

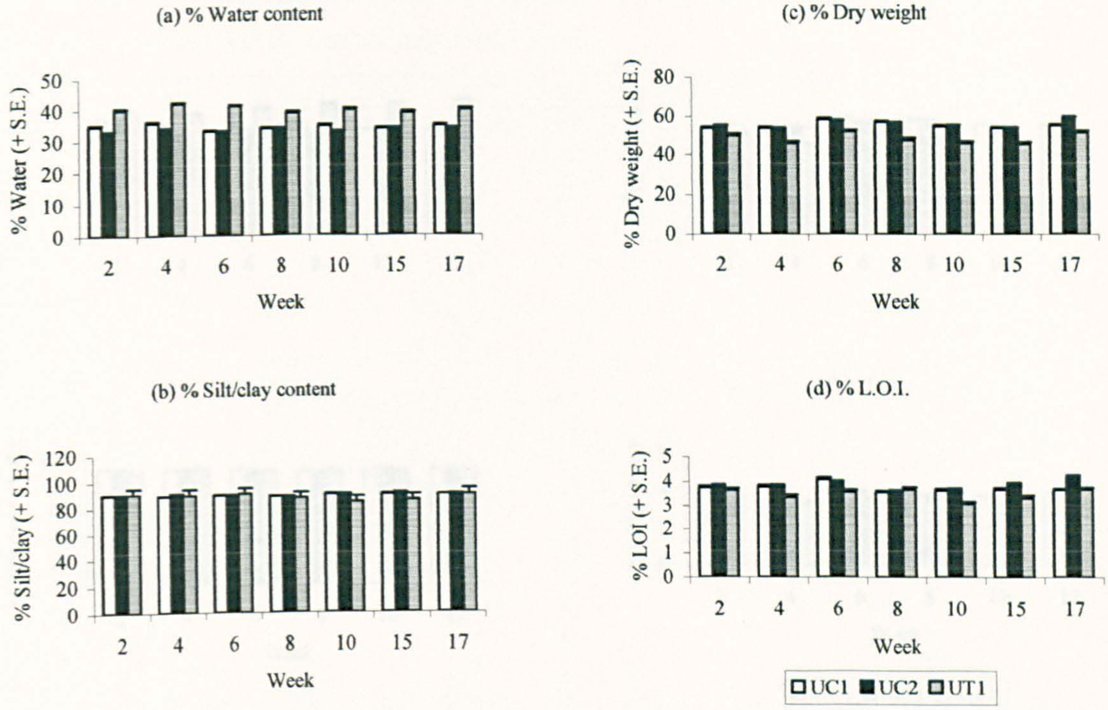


Figure 4.4 (a-d): Changes in upper-shore transect 1 sediment variables (a) mean sediment water content, (b) mean silt/clay content, (c) dry weight content and (d) % LOI. Note transect 1 upper-shore control abbreviations: defaunated mudflat control (UC1), established mudflat control (UC2).

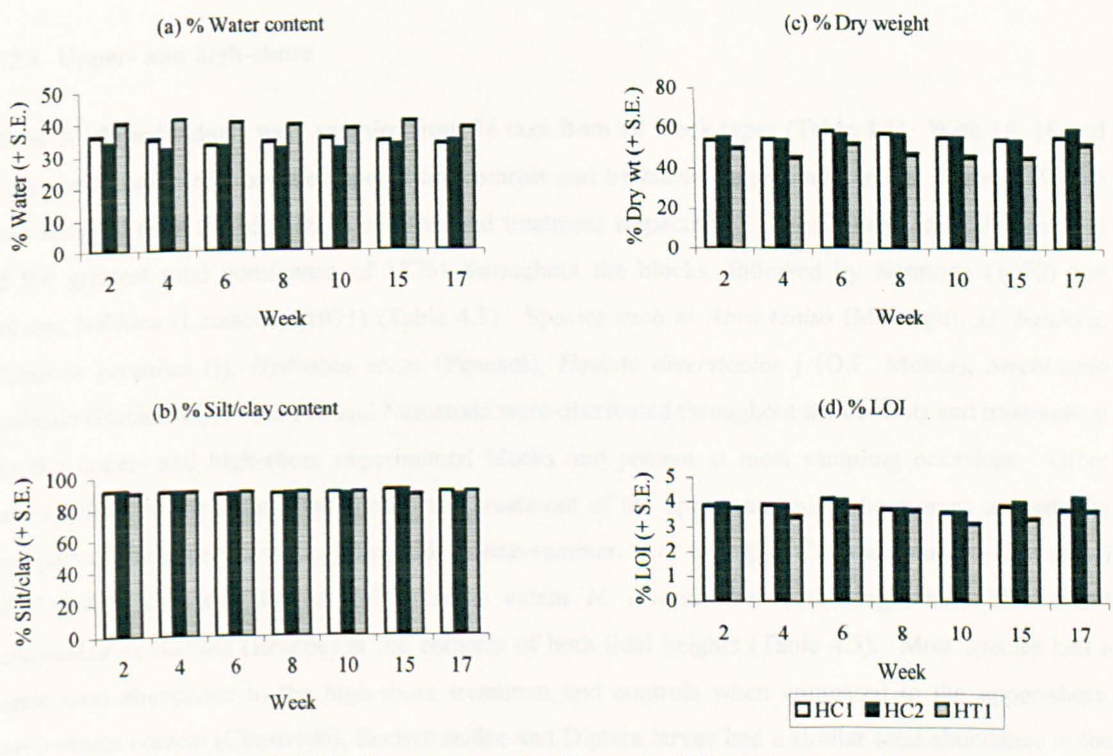


Figure 4.5 (a-d): Changes in high-shore transect 1 sediment variables (a) mean sediment water content, (b) mean silt/clay content, (c) dry weight content and (d) % LOI. Note transect 1 high-shore control abbreviations: defaunated mudflat control (HC1), established mudflat control (HC2).

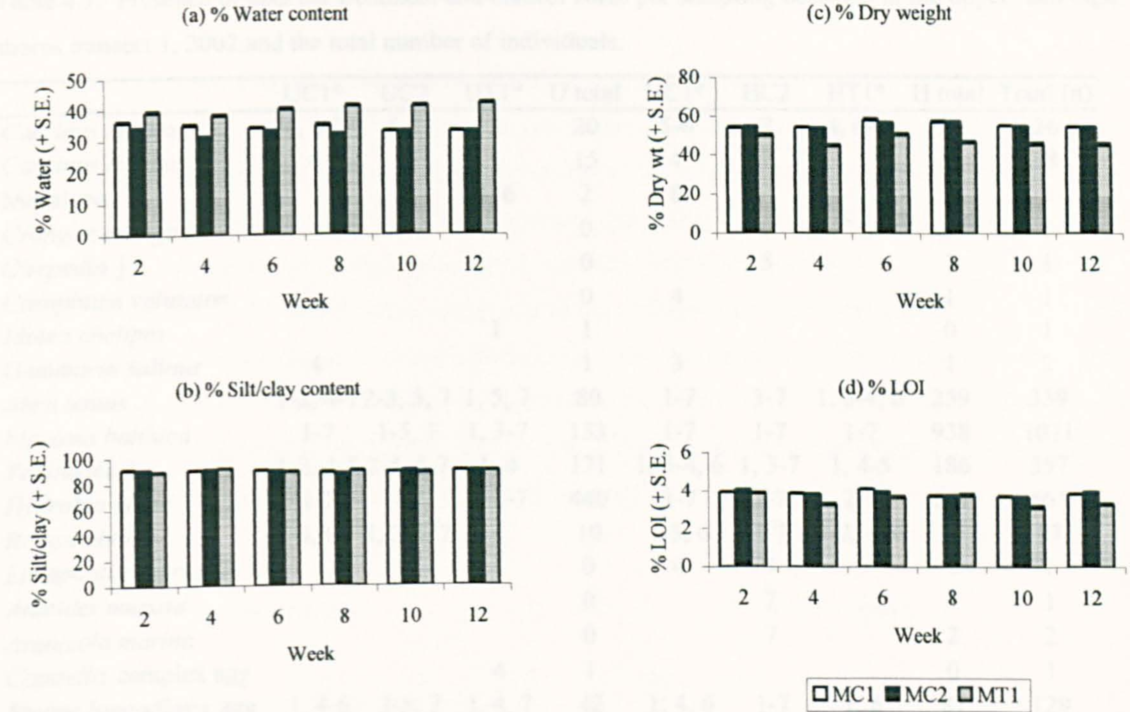


Figure 4.6 (a-d): Changes in mid-shore transect 2 sediment variables (a) mean sediment water content, (b) mean silt/clay content, (c) dry weight content and (d) % LOI. Note transect 2 mid-shore control abbreviations: defaunated mudflat control (MC1), established mudflat control (MC2).

4.3.2 Biota transect 1, 2002

4.3.2.1 Upper- and high-shore

In total 20180 individuals were sampled from 34 taxa from all block types (Table 4.3). With 18, 18 and 21 taxa being sampled from the upper-shore controls and treatment respectively and 21, 24 and 19 taxa being sampled from the high-shore controls and treatment respectively. *Tubificoides benedii* (Udekem) had the greatest total dominance of 13761 throughout the blocks, followed by Nemtoda (1270) and *Macoma balthica* (Linnaeus) (1071) (Table 4.3). Species such as *Abra tenius* (Montagu), *M. balthica*, Tellinacea juveniles (j), *Hydrobia ulvae* (Pennant), *Hediste diversicolor* j (O.F. Muller), *Streblospio shrubsolii* (Buchanan), *T. benedii* and Nematoda were distributed throughout the controls and treatment at both the upper- and high-shore experimental blocks and present at most sampling occasions. Other species colonized the defaunated control and treatment of the upper- and high-shore areas towards the latter part of the experiment i.e. from mid- to late-summer. For example, *Carcinus maenas* (Linnaeus) and *Polydora cornuta* (Bosch) and to some extent *H. diversicolor* at the high-shore blocks and *Manayunkia aestuarina* (Bourne) at the controls of both tidal heights (Table 4.3). Most species had a greater total abundance in the high-shore treatment and controls when compared to the upper-shore. *Heterochaeta costata* (Claparède), Enchytraeidae and Diptera larvae had a similar total abundance at the upper- and high-shores. Overall the high-shore treatment and controls had the highest total abundance of 14601 when compared to the upper-shore (5579). Also the species richness (29) was greater at the high-shore when compared to the upper-shore (25).

Table 4.3: Presence of taxa per treatment and control cores per sampling occasion at the upper- and high-shores transect 1, 2002 and the total number of individuals.

	UC1*	UC2	UT1*	U total	HC1*	HC2	HT1*	H total	Total (n)
Carcinus maenas	4, 6-7	5-7	5	20	5-6	7	4, 6-7	6	26
Carcinus maenas j	4			15	4	7		13	28
Megalopa			4, 6	2	6			1	3
Crangon crangon				0		6		1	1
Cirrpedia j				0		5		1	1
Corophium volutator				0	4			1	1
Idotea chelipes			1	1				0	1
Gammarus salinus	4			1	3			1	2
Abra tenuis	1-2, 4-7	2-3, 5, 7	1, 5, 7	80	1-7	3-7	1, 3-4, 6	259	339
Macoma balthica	1-7	1-5, 7	1, 3-7	133	1-7	1-7	1-7	938	1071
Tellinacea j	1-2, 4-5	2-4, 6-7	1, 4	171	1, 3-4, 6	1, 3-7	1, 4-5	186	357
Hydrobia ulvae	1-7	1-7	1, 3-7	440	1-7	1-7	2-7	221	661
Retusa obtusa	4, 6	1, 3-4, 7		10	1-3, 6	1-7	1-2, 4, 6	77	87
Limapontia depressa				0	4	4		1	1
Anatides mucosa				0		7		1	1
Arenicola marina				0		7		2	2
Capitella complex agg			4	1				0	1
Eteone longa/flava agg	1, 4-6	3-5, 7	1, 4, 7	42	1, 4, 6	1-7	1, 6	87	129
Hediste diversicolor	1, 3-7	1, 3-6	1, 3-7	291	4-7	3-7	4-7	204	495
Hediste diversicolor j	1-7	3-6	1, 3, 5-7	343	1, 3-7	1, 3, 5-7	1, 3-7	170	513
Manayunkia aestuarina	3-7	3-6	1, 4, 7	72	5-6	4, 7	1, 4, 6-7	21	93
Nephyts hombergii				0		3	2	5	5
Nephyts j				0		7		1	1
Polydora cornuta	4-7	4-5, 7	6-7	211	4-7	5-7	5, 7	206	417
Pygospio elegans	3-7	3-7	1, 4, 6-7	138	1, 3-6	1-7	1, 3, 5	219	357
Streblospio shrubsolii	1, 4-7	3-5, 7	1, 3-7	242	1, 3-7	1-7	1, 4-7	208	450
Tharyx "A"				0	6-7	4-5, 7	1, 5	10	10
Tubificoides benedii	1, 3-7	1, 3-7	1, 3-7	2785	1, 3-7	1-7	1, 3-7	10976	13761
Heterochaeta costata	1, 4		4, 6	15				0	15
Enchytraeidae	1, 3, 7		1, 6	25			6	1	26
Nemertea		6-7	4	6	6	7	2, 4-5, 7	7	13
Nematoda	1-2, 4-7	2-7	1-2, 4-7	499	1-4, 6-7	1-7	2, 4-5, 7	771	1270
Insecta	5, 7	4-5, 7	5, 7	10		5, 7	7	4	14
Chronomid larvae		5		1				0	1
Diptera larvae		5-6		17				0	17
Arachnid			4, 7	8	7			2	10
Total number of species	18	18	21	25	21	24	19	29	

1 indicates the presence in that treatment or control after 2 wks, 2=4 wks, 3=6 wks, 4=8 wks, 5=10 wks, 6=15 wks, 7=17 wks. The total number (*n*) of individuals sampled of each taxa throughout the experiment is given in the last column. * Disk present between mudflat surface and treatment deposition. Refer to Figures 4.4 and 4.5 for control abbreviations.

The descriptive statistics of each species present in the treatment and controls per layer at the upper- and high-shore areas were determined (Appendices). Additionally, meio-faunal and juvenile macro-faunal samples were taken alongside the macro-faunal samples at each tidal height; these samples were preserved and stored for further analysis at a later date, as the macro-faunal response was the primary concern of the study.

4.3.2.1.1 Univariate community indices of the upper-shore

The mean abundance of total individuals at the upper-shore was generally greater in the controls each week except for wk 2 when initial colonization was highest in the treatment (Figure 4.7 a). The initial colonization of the treatment at the upper-shore was high with 13 species present when compared to the defaunated and mudflat controls with 11 and 5 species respectively. Species colonization declined by wk 4 but began to recover by wk 6, especially in the controls. The mudflat control had a greater number of species during wks 6, 10 and 17 when compared to the defaunated control and the treatment; also the treatment had a greater number of species during wk 8 and 15 when compared to the mudflat control (Figure 4.7 b). Initially, species diversity was greatest in the treatment, the controls had a higher species diversity indices overall (Figure 4.7 c). During wk 2 Pielou's evenness was higher in the treatment (Figure 4.7 d). Subsequent evenness was greater in the controls.

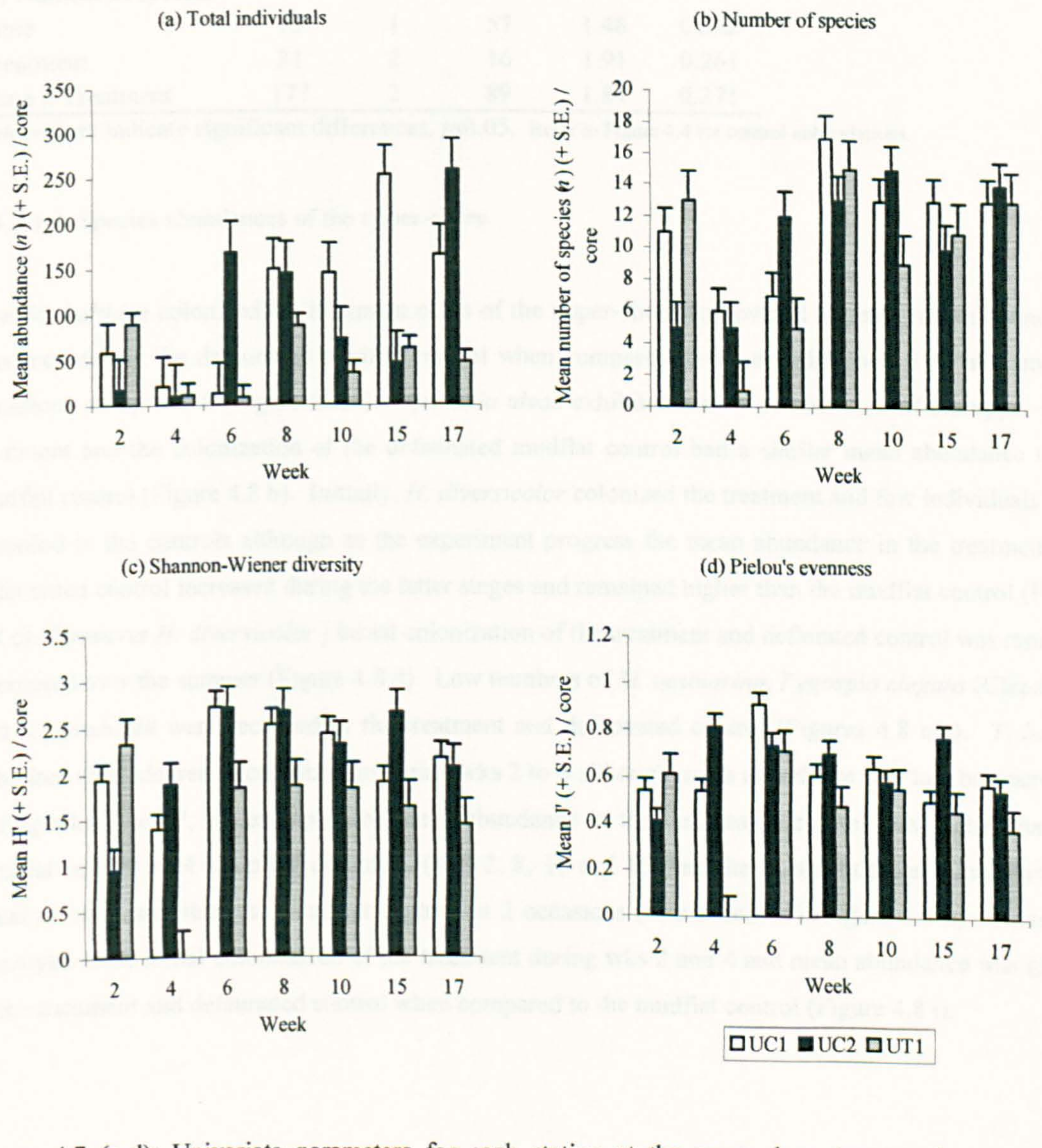


Figure 4.7 (a-d): Univariate parameters for each station at the upper-shore transect 1 per core per sampling occasion (+ S.E., $n = 3$). Refer to Figure 4.4 for control abbreviations.

The mean abundance of total individuals and number of species at the upper-shore were not significantly different between time or between treatments when comparing the controls and treatment 1 (Table 4.4) although repeated contrasts revealed significant interactions between treatments and time however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Table 4.4).

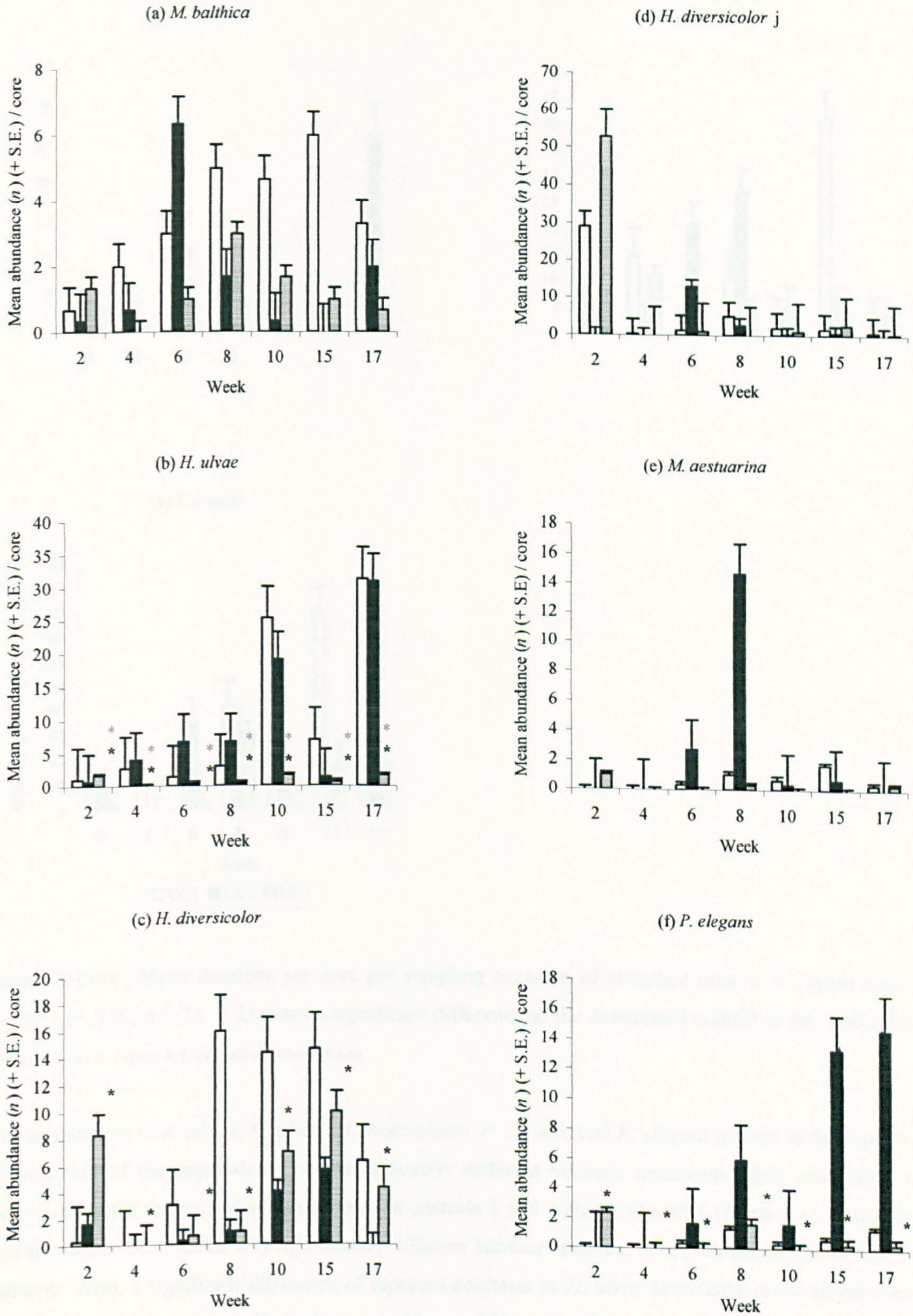
Table 4.4: Repeated measures ANOVA of univariate indices at the upper-shore Control 1, Control 2 & Treatment 1 2002.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time	129094	2	67465	3.95	0.118
Treatment	48451	2	24225	3.94	0.113
Time x Treatment	159750	2	101379	3.93	0.139
(b) Number of species					
Time	75	1	57	1.48	0.342
Treatment	31	2	16	1.91	0.261
Time x Treatment	177	2	89	1.84	0.271

Bold values indicate significant differences, $p<0.05$. Refer to Figure 4.4 for control abbreviations.

4.3.2.1.2 Species abundances of the upper-shore

Few *M. balthica* colonized the treatment cores of the upper-shore and overall a greater mean abundance was recorded in the defaunated mudflat control when compared to the mudflat control on all sampling occasions except wk 6 (Figure 4.8 a). *Hydrobia ulvae* exhibited a slow colonization of the upper-shore treatment and the colonization of the defaunated mudflat control had a similar mean abundance to the mudflat control (Figure 4.8 b). Initially, *H. diversicolor* colonized the treatment and few individuals were recorded in the controls although as the experiment progress the mean abundance in the treatment and defaunated control increased during the latter stages and remained higher than the mudflat control (Figure 4.8 c). However *H. diversicolor* j initial colonization of the treatment and defaunted control was rapid but decreased over the summer (Figure 4.8 d). Low numbers of *M. aestuarina*, *Pygospio elegans* (Claparède) and *S. shrubsolii* were recorded in the treatment and defaunated control (Figures 4.8 e-g). *T. benedii* exhibited some degree of colonization during wks 2 to 6 although mean abundance was low but increased during wks 8 to 17, for example, the mean abundance in the defaunated control was higher than the mudflat control on 4 sampling occasions (wks 2, 8, 10 and 15) and the treatment mean abundance was equal to or greater than the mudflat control on 2 occasions (wks 8 and 15) (Figure 4.8 h). Nematoda displayed some initial colonization of the treatment during wks 2 and 4 and mean abundance was greater in the treatment and defaunated control when compared to the mudflat control (Figure 4.8 i).


(a) M. balthica
Mean abundance (n) (+ S.E.) / core
8
6
4
2
0
2
4
6
8
10
15
17
Week
(b) H. ulvae
Mean abundance (n) (+ S.E.) / core
40
35
30
25
20
15
10
5
0
2
4
6
8
10
15
17
Week
(c) H. diversicolor
Mean abundance (n) (+ S.E.) / core
20
18
16
14
12
10
8
6
4
2
0
2
4
6
8
10
15
17
Week
(d) H. diversicolor j
Mean abundance (n) (+ S.E.) / core
70
60
50
40
30
20
10
0
2
4
6
8
10
15
17
Week
(e) M. aestuarina
Mean abundance (n) (+ S.E) / core
18
16
14
12
10
8
6
4
2
0
2
4
6
8
10
15
17
Week
(f) P. elegans
Mean abundance (n) (+ S.E.) core
18
16
14
12
10
8
6
4
2
0
2
4
6
8
10
15
17
Week

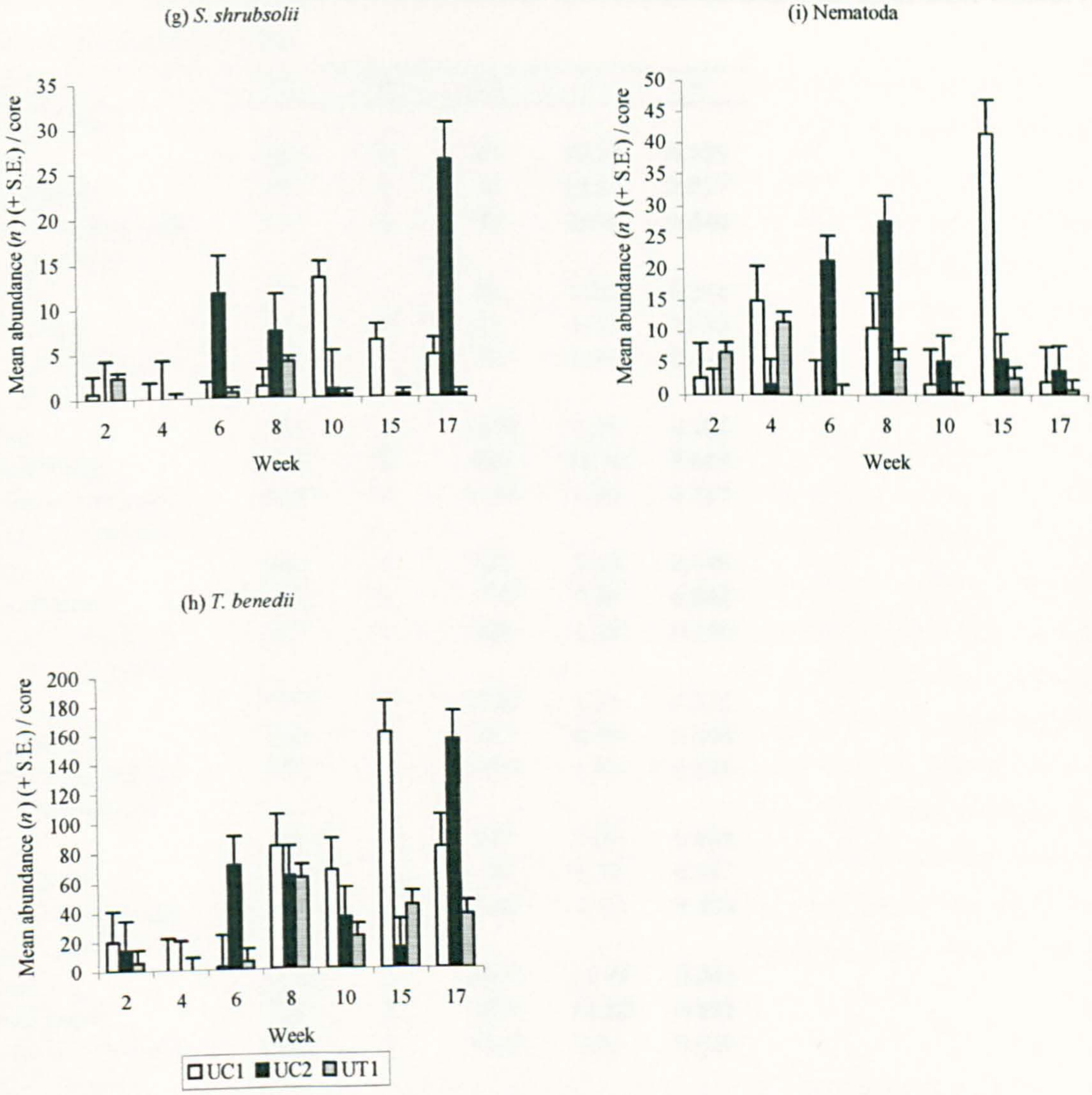


Figure 4.8 (a-i): Mean densities per core per sampling occasion of abundant taxa at the upper-shore transect 1 (+ S.E., $n = 3$). * Denotes a significant difference to the defaunated control or the * mudflat control. Refer to Figure 4.4 for control abbreviations.

Mean abundances of *A. tenuis*, *H. ulvae*, *H. diversicolor*, *P. cornuta* and *P. elegans* present in the controls and treatment of the upper-shore were significantly different between treatments when comparing a repeated measures analysis of variance between controls 1 and 2 and treatment 1 (Table 4.5). Also the mean abundance of *A. tenuis* was significantly different between time and during an interaction of time x treatment. Also, a significant difference of repeated contrasts of *H. ulvae* abundance occurred between the controls and treatment. Similarly, a significant difference of *H. diversicolor* mean abundance occurred between control 2 and treatment 1, also a significant difference occurred between wks 15 and 17, in general abundance was greater in the treatment when compared to the mudflat control each week (Figure 4.8 c). Repeated contrasts revealed significant interactions between time and treatment however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Table 4.5).

Table 4.5: Repeated measures ANOVA of abundance data for common taxa at the upper-shore Control 1, Control 2 & Treatment 1 2002.

Source	SS	DF	MS	F	P
(a) *A. tenuis*					
Time	**102**	**2**	**67**	**12.62**	**0.035**
Treatment	**42**	**2**	**21**	**13.57**	**0.017**
Time x Treatment	**173**	**2**	**92**	**8.56**	**0.040**
(b) *M. balthica*					
Time	57	1	50	2.20	0.268
Treatment	63	2	31	1.42	0.342
Time x Treatment	107	1	72	1.49	0.338
(c) *H. ulvae*					
Time	3417	2	2234	3.35	0.168
Treatment	**1178**	**2**	**589**	**12.70**	**0.019**
Time x Treatment	1693	1	1248	1.90	0.287
(d) *H. diversicolor*					
Time	746	1	501	3.90	0.146
Treatment	**358**	**2**	**179**	**7.59**	**0.044**
Time x Treatment	553	1	484	1.20	0.390
(e) *H. diversicolor* j					
Time	5359	1	5229	1.31	0.371
Treatment	334	2	167	0.59	0.598
Time x Treatment	3877	1	3495	1.53	0.339
(f) *M. aestuarina*					
Time	193	1	177	1.09	0.408
Treatment	72	2	36	1.35	0.357
Time x Treatment	341	1	316	1.10	0.405
(g) *P. cornuta*					
Time	1194	1	1067	11.24	0.068
Treatment	**702**	**2**	**351**	**11.82**	**0.021**
Time x Treatment	1135	1	1037	2.81	0.229
(h) *P. elegans*					
Time	259	2	131	2.59	0.191
Treatment	**305**	**2**	**153**	**8.73**	**0.035**
Time x Treatment	468	2	246	2.58	0.196
(i) *S. shrubsolii*					
Time	630	1	486	3.01	0.203
Treatment	321	2	160	4.87	0.085
Time x Treatment	1558	2	1000	3.19	0.174
(j) *T. benedii*					
Time	64039	1	48864	9.55	0.064
Treatment	13336	2	6668	5.12	0.079
Time x Treatment	59698	2	33362	4.92	0.095
(k) Nematoda					
Time	1889	1	1587	1.08	0.412
Treatment	510	2	255	0.53	0.626
Time x Treatment	4385	1	3213	1.55	0.331

Bold values indicate significant differences, $p<0.05$. Refer to Figure 4.4 for control abbreviations.

4.3.2.1.3 Biomass of the upper-shore community

The mean wet weight biomass of *M. balthica* was highest in the defaunated control between wks 8 to 15. Also, the defaunated control matched the mudflat control biomass from wks 4 to 6 and the mudflat control had the highest biomass initially and at the end of the experiment (Figure 4.9 a). The treatment, however, had a higher biomass than the mudflat control at wks 8, 10 and 15. The defaunated control had a total mean wet weight biomass of *M. balthica* (0.5 g) and was greater than the mudflat control (0.2 g) and the treatment (0.2 g). *Hediste diversicolor* mean wet weight biomass was low initially however between wks 8 to 17 the defaunated control had the greatest biomass (Figure 4.9 b). From wks 10 to 17 the treatment had a higher biomass than the control and overall the defaunated control had the highest total mean wet weight biomass (2.3 g) over seventeen weeks when compared to the treatment (0.4 g) and the mudflat control (0.3 g). Initially the mean wet weight biomass of *H. diversicolor* j was highest in the treatment. However, biomass decreased from wks 4 to 17 and the treatment had the highest total mean wet weight biomass (0.02 g) when compared to the controls (0.01 g) (Figure 4.9 c). Initially *T. benedii* wet weight biomass was low and the defaunated control had the highest biomass between wks 8 and 15 also the mudflat control was greatest at wk 17 and both the controls had the highest total mean wet weight biomass (0.2 g) followed by the treatment (0.1 g) (Figure 4.9 d). Nematoda mean wet weight biomass was greatest in the treatment between wks 2 to 4 and the defaunated control had the highest biomass overall at wk 8, similarly the mudflat control had the highest biomass during wks 6, 10 and 17 (Figure 4.9 e). The controls had the greatest total mean biomass of Nematoda (0.002 g) at the end of seventeen weeks and the treatment was less (0.001 g). Overall, *H. diversicolor* had the highest total mean wet weight biomass of 3.0 g at the end of seventeen weeks, followed by *M. balthica* (0.9 g), *T. benedii* (0.5 g), *H. diversicolor* j (0.04 g) and lastly, Nematoda (0.004 g).

The AFDW of *M. balthica* followed a similar trend to the mean abundance between wks 8 to 15 when the highest AFDW occurred in the upper-shore defaunated control however, the AFDW differed between wks 2 to 6 when compared to the mean abundance trend (Figure 4.10 a). The upper-shore mudflat control had the highest AFDW of *M. balthica* initially, although by wk 6 the defaunated control had the greatest AFDW. The AFDW of *H. diversicolor* followed a similar trend to the mean abundance of the upper-shore controls and treatment (Figure 4.10 b-c). The AFDW of *T. benedii* differed at wk 8 when compared to the mean abundance and a higher AFDW occurred in the treatment (Figure 4.10 d). The AFDW of Nematoda was similar to the mean abundance between wks 2 and 6 but differed between wks 8 to 17 both the controls and the treatment had an equal AFDW. During wks 10 and 17 the mudflat control and treatment had an equal AFDW of Nematoda however, at wk 15 the mudflat control had an increased AFDW and the defaunated control and treatment had the same AFDW (Figure 4.10 e).

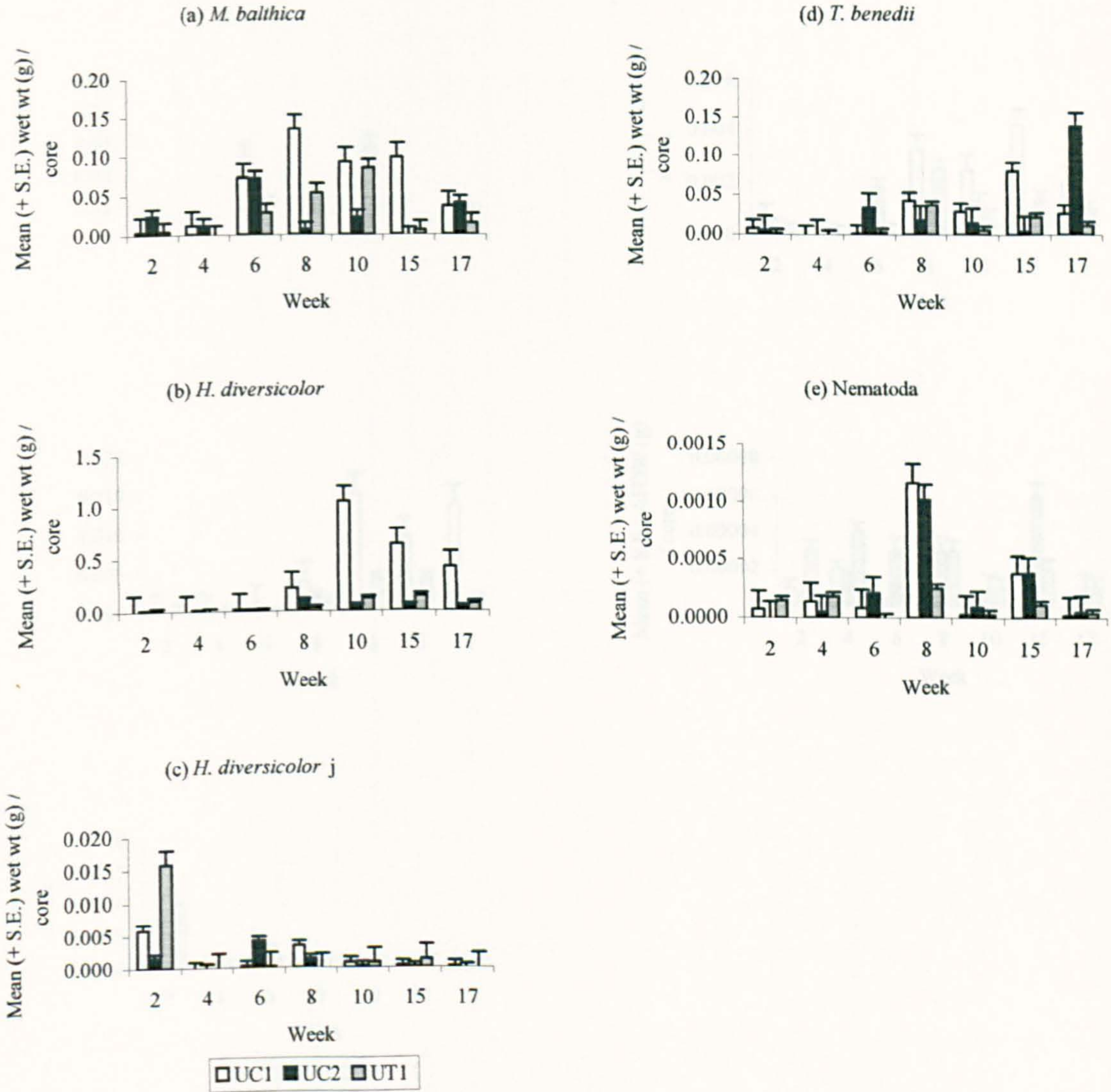


Figure 4.9 (a-e): Mean wet weight biomass per core per sampling occasion of abundant taxa at the upper-shore (+ S.E., n=3). Refer to Figure 4.4 for control abbreviations.

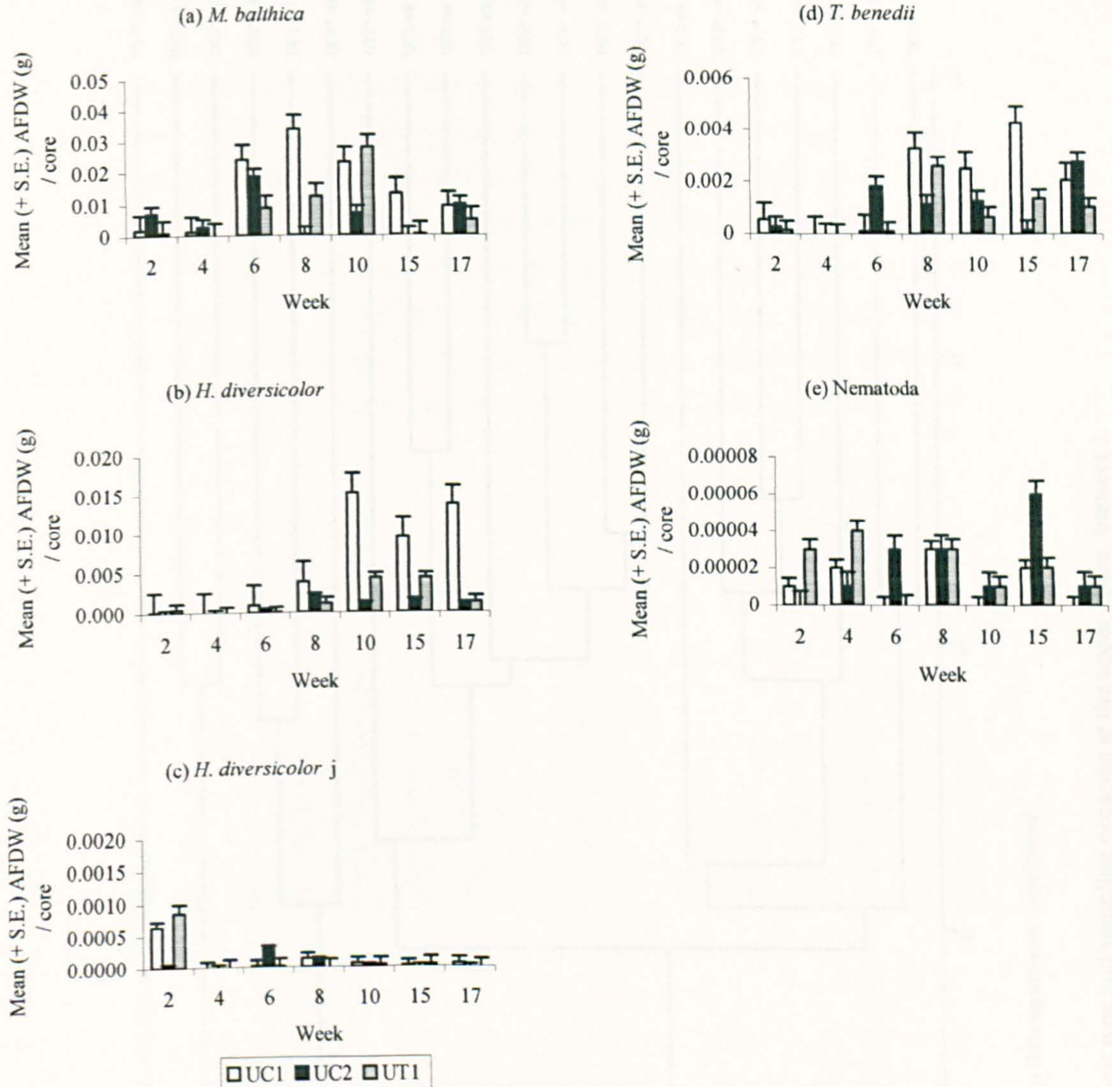


Figure 4.10 (a-e): Mean AFDW biomass per core per sampling occasion of abundant taxa at the upper-shore (+ S.E., n=3). Refer to Figure 4.4 for control abbreviations.

4.3.2.1.4 Classification analysis of the upper-shore controls and treatment communities

The community structure in each treatment and control communities at the upper-shore were divided into three groups, one formed by treatment and control communities of the early stages of the experiment (Figure 4.11). The second group consisted primarily of control communities from wks 6 to 17, whilst the final group included predominantly treatment and mudflat control communities from the latter part of the experiment.

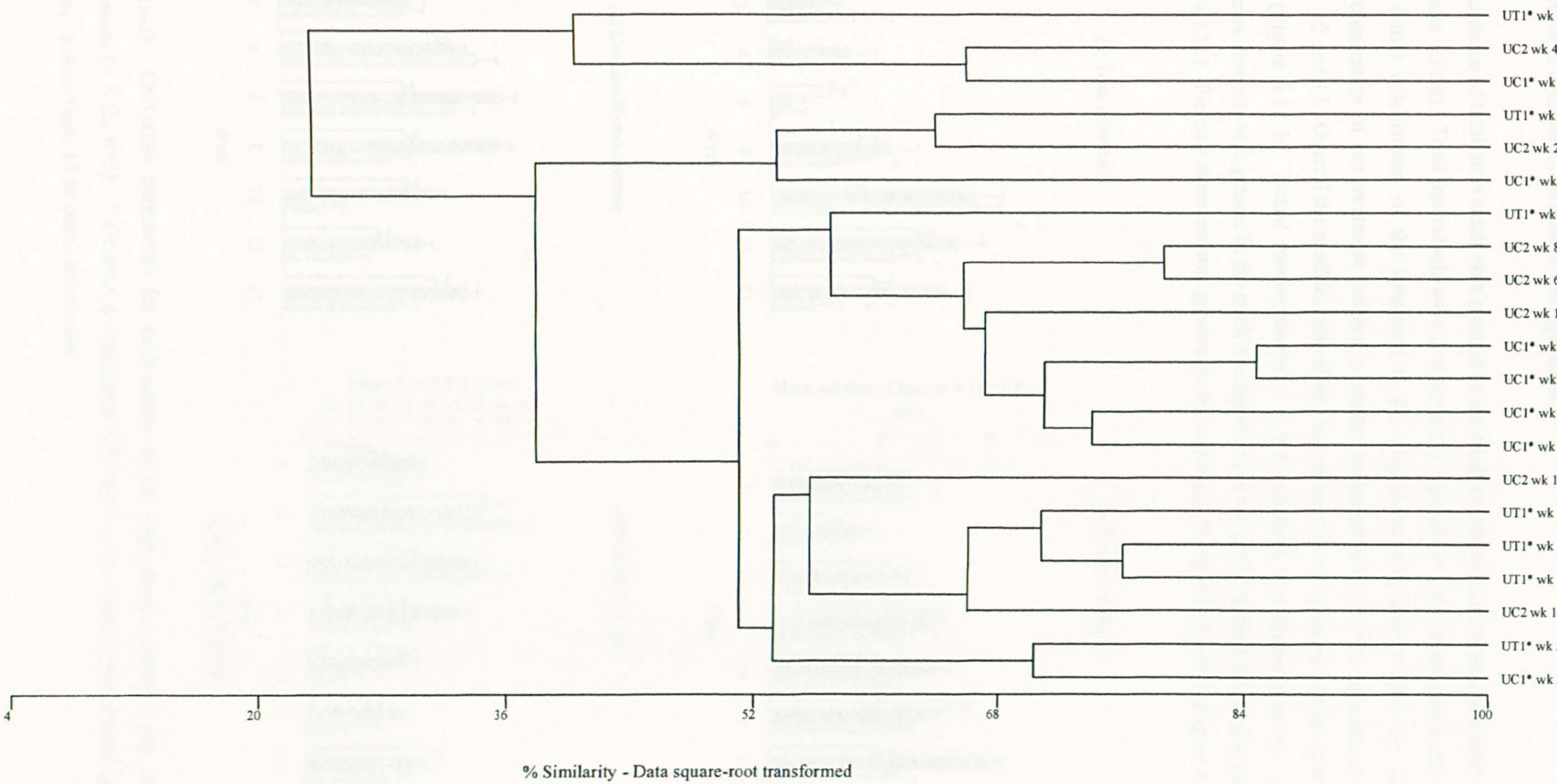


Figure 4.11: Assemblage composition similarity dendrogram of treatment type and sampling occasion at the upper-shore, transect 1.

4.3.2.1.5 Univariate community indices of the high-shore

The mean abundance of total individuals was greatest in the mudflat control each week apart from wks 2, 6 and 10 (Figure 4.12 a). Total individuals were greater at the high-shore when compared to the upper-shore. The initial colonization of the treatment at the high-shore was greater than the controls. Subsequent colonization of the treatment reached a similar or higher level to the defaunated control during wks 4, 10 and 17. Overall the mudflat control number of species was greatest except during wks 2, 8 and 15 (Figure 4.12 b). Initial species diversity in the treatment was higher than the controls although, species diversity was greater in the mudflat control when compared to the treatment from wks 8 to 17 (Figure 4.12 c). Pielou's evenness was greatest in the treatment during wks 4 and 6 (Figure 4.12 d).

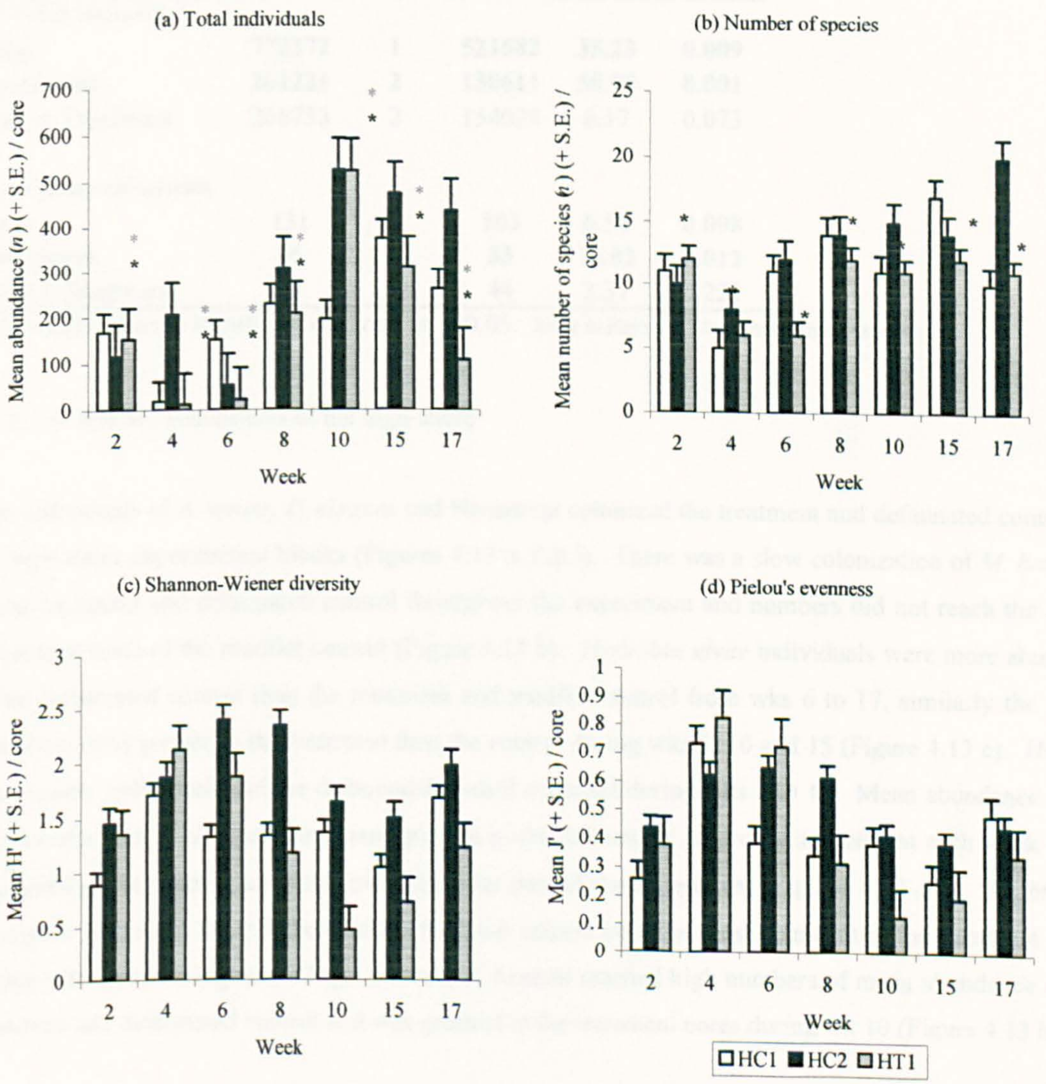


Figure 4.12 (a-d): Univariate parameters for each station at the high-shore transect 1 per core per sampling occasion (+ S.E., n=3). * Denotes a significant difference to the defaunated control or the * mudflat control. Refer to Figure 4.5 for control abbreviations.

The mean abundance of total individuals at the high-shore transect 2 were significantly different between time and between treatments, also the number of species were significantly different between treatments when comparing a repeated measures analysis of variance between the controls and treatment 1 (Table 4.6). Repeated contrasts of total individuals revealed a significant difference between wks 2 with 4, wks 6 with 8 and wks 15 with 17 and a significant difference between the controls and treatment 1 occurred (Appendix 2 Table 4.6). Repeated contrasts of the number of species revealed a significant difference between the control 2 and treatment 1 (Appendix 2 Table 4.6).

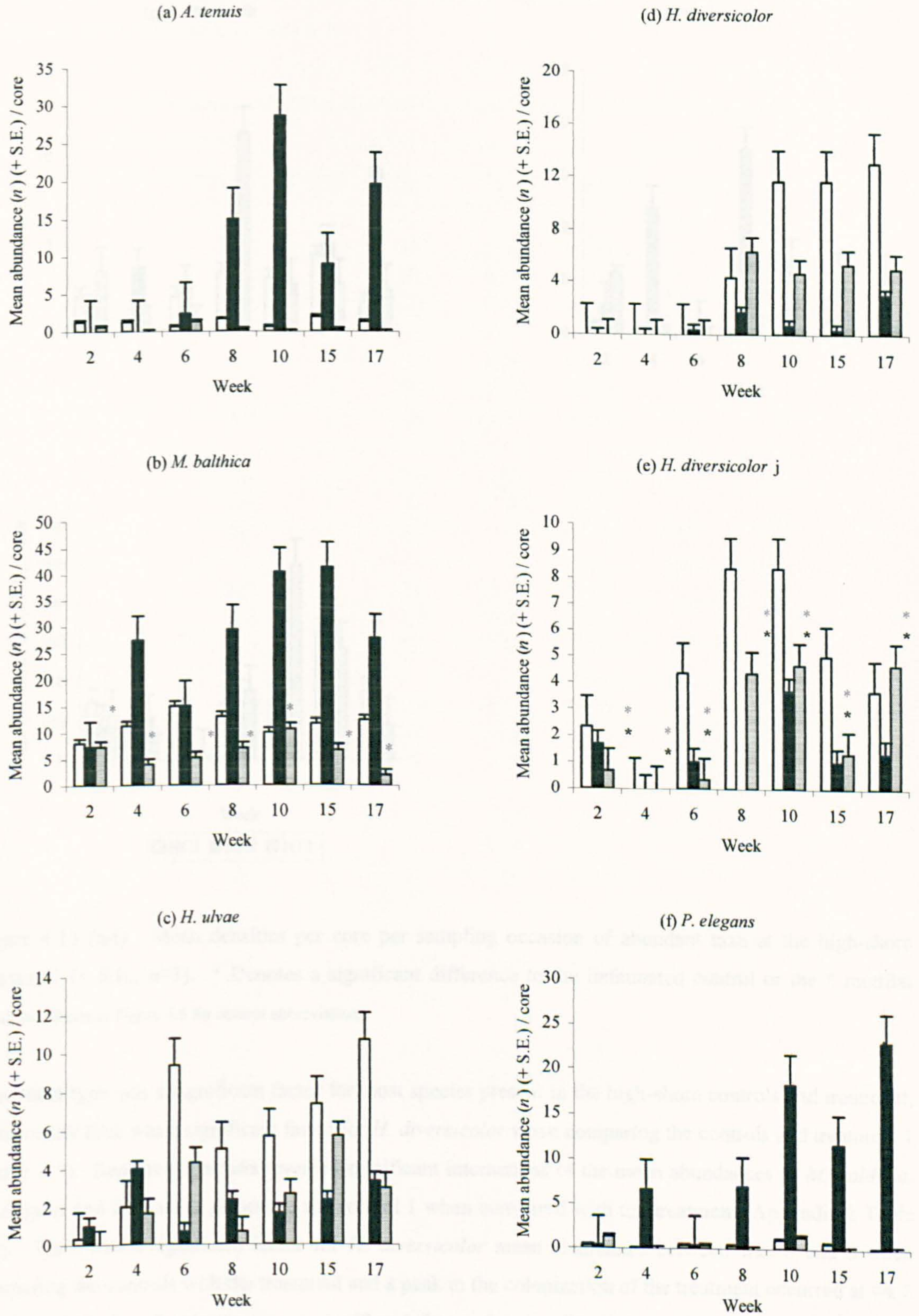
Table 4.6: Repeated measures ANOVA of univariate indices at the high-shore Control 1, Control 2 & Treatment 1 2002.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time	**772372**	**1**	**521682**	**35.23**	**0.009**
Treatment	**261221**	**2**	**130611**	**50.95**	**0.001**
Time x Treatment	268733	2	154029	6.17	0.073
(b) Number of species					
Time	131	1	103	6.59	0.098
Treatment	**66**	**2**	**33**	**16.02**	**0.012**
Time x Treatment	77	2	44	2.37	0.221

Bold values indicate significant differences, $p<0.05$. Refer to Figure 4.5 for control abbreviations.

4.3.2.1.6 Species abundances of the high-shore

Few individuals of *A. tenuis*, *P. elegans* and Nematoda colonized the treatment and defaunated control of the high-shore experimental blocks (Figures 4.13 a, f & i). There was a slow colonization of *M. balthica* in the treatment and defaunated control throughout the experiment and numbers did not reach the mean abundance level of the mudflat control (Figure 4.13 b). *Hydrobia ulvae* individuals were more abundant in the defaunated control than the treatment and mudflat control from wks 6 to 17, similarly the mean abundance was greater in the treatment than the control during wks 6, 10 and 15 (Figure 4.13 c). *Hediste diversicolor* colonization of the defaunated control occurred during wks 8 to 17. Mean abundance of *H. diversicolor* and *H. diversicolor* j were greatest in the defaunated control and treatment each week when compared to the mudflat control during the latter part of the experiment (Figures 4.13 d-e). *Streblospio shrubsolii* colonized the treatment and defaunated control and was most abundant in the treatment cores during wks 2 and 8 (Figure 4.13 g). Overall, *T. benedii* reached high numbers of mean abundance in the treatment and defaunated control and was greatest in the treatment cores during wk 10 (Figure 4.13 h).


(a) A. tenuis
Mean abundance (n) (+ S.E.) / core
0
5
10
15
20
25
30
35
2
4
6
8
10
15
17
Week
(d) H. diversicolor
Mean abundance (n) (+ S.E.) / core
0
4
8
12
16
20
2
4
6
8
10
15
17
Week
(b) M. balthica
Mean abundance (n) (+ S.E.) / core
0
5
10
15
20
25
30
35
40
45
50
2
4
6
8
10
15
17
Week
(e) H. diversicolor j
Mean abundance (n) (+ S.E.) / core
0
1
2
3
4
5
6
7
8
9
10
2
4
6
8
10
15
17
Week
(c) H. ulvae
Mean abundance (n) (+ S.E.) / core
0
2
4
6
8
10
12
14
2
4
6
8
10
15
17
Week
(f) P. elegans
Mean abundance (n) (+ S.E.) / core
0
5
10
15
20
25
30
2
4
6
8
10
15
17
Week

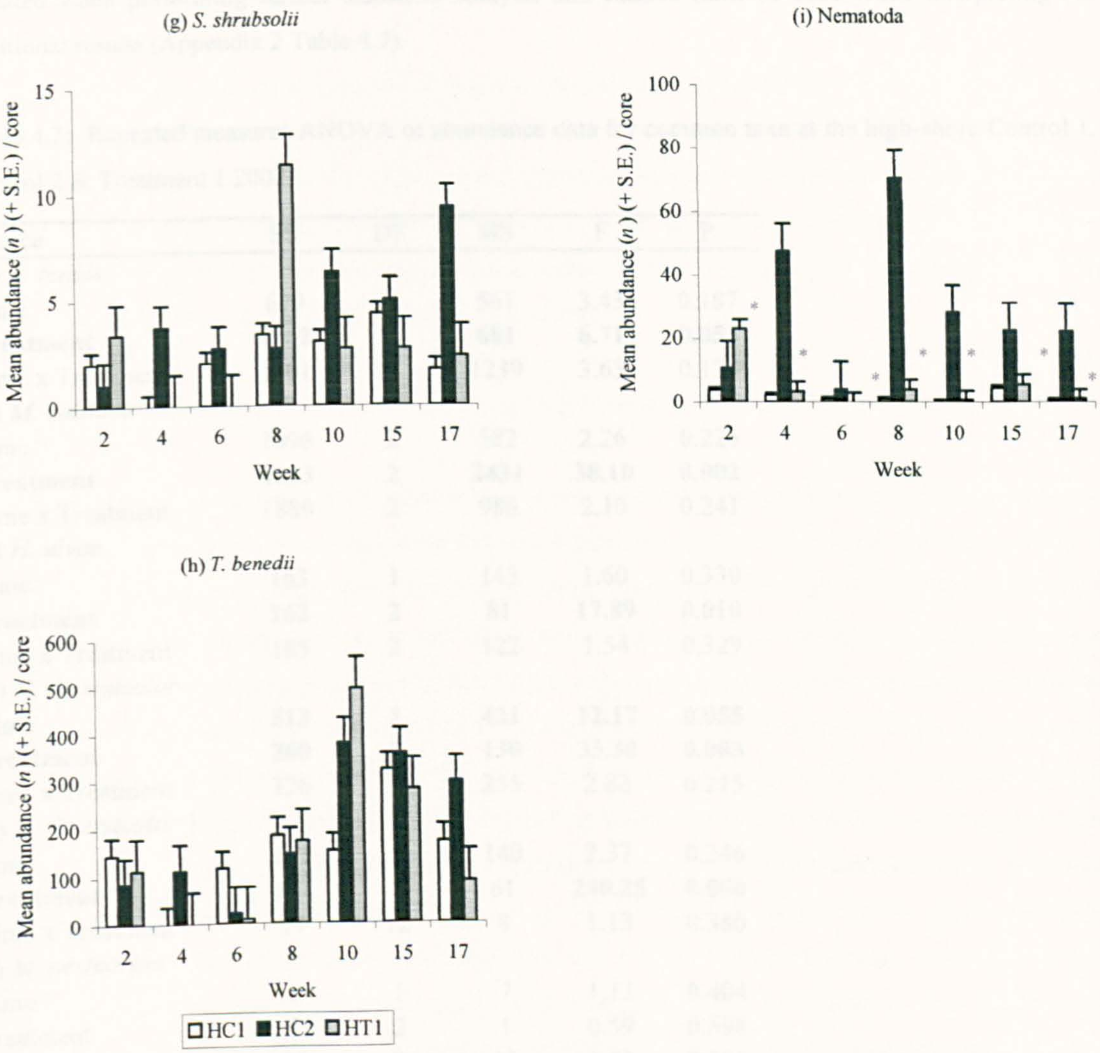


Figure 4.13 (a-i): Mean densities per core per sampling occasion of abundant taxa at the high-shore transect 1 (+ S.E., n=3). * Denotes a significant difference to the defaunated control or the * mudflat control. Refer to Figure 4.5 for control abbreviations.

Treatment type was a significant factor for most species present in the high-shore controls and treatment, additionally time was a significant factor for *H. diversicolor* when comparing the controls and treatment 1 (Table 4.7). Repeated contrasts revealed significant interactions of the mean abundances of *M. balthica*, *P. elegans* and Nematoda present in the control 1 when compared with the treatment (Appendix 2 Table 4.7). Time was a significant factor for *H. diversicolor* mean abundance between wks 6 and 8 when comparing the controls with the treatment and a peak in the colonization of the treatment occurred at wk 8 (Figures 4.13 d). Treatment was a significant factor for the distribution of *H. diversicolor* j when comparing the controls with the treatment (Appendix 2 Table 4.7) and the defaunated control had a greater mean abundance than the treatment during wks 8, 10 and 15 however by wk 17 mean abundance had increased in the treatment and was less in the defaunated control (Figure 4.13 e). Repeated contrasts revealed significant interactions between time and treatment however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Table 4.7).

Table 4.7: Repeated measures ANOVA of abundance data for common taxa at the high-shore Control 1, Control 2 & Treatment 1 2002.

Source	SS	DF	MS	F	P
(a) *A. tenuis*					
Time	679	1	561	3.43	0.187
Treatment	**1362**	**2**	**681**	**6.71**	**0.053**
Time x Treatment	1501	1	1239	3.63	0.178
(b) *M. balthica*					
Time	1096	2	582	2.26	0.226
Treatment	**4863**	**2**	**2431**	**38.10**	**0.002**
Time x Treatment	1889	2	986	2.10	0.241
(c) *H. ulvae*					
Time	163	1	143	1.60	0.330
Treatment	**162**	**2**	**81**	**17.89**	**0.010**
Time x Treatment	185	2	122	1.54	0.329
(d) *H. diversicolor*					
Time	**513**	**1**	**421**	**12.17**	**0.055**
Treatment	**260**	**2**	**130**	**33.30**	**0.003**
Time x Treatment	326	1	255	2.82	0.215
(e) *H. diversicolor* j					
Time	181	1	140	2.37	0.246
Treatment	**122**	**2**	**61**	**240.25**	**0.000**
Time x Treatment	97	12	8	1.13	0.380
(f) *M. aestuarina*					
Time	8	1	7	1.13	0.404
Treatment	1	2	1	0.59	0.598
Time x Treatment	20	2	10	1.61	0.309
(g) *P. cornuta*					
Time	2916	1	2904	6.74	0.121
Treatment	689	1	689	4.87	0.158
Time x Treatment	3448	1	3402	4.82	0.158
(h) *P. elegans*					
Time	450	2	279	3.49	0.155
Treatment	**1189**	**2**	**594**	**104.88**	**0.000**
Time x Treatment	901	2	550	3.08	0.176
(i) *S. shrubsolii*					
Time	155	2	89	1.97	0.264
Treatment	**44**	**2**	**22**	**17.06**	**0.011**
Time x Treatment	283	1	206	2.03	0.273
(j) *T. benedii*					
Time	789077	1	662569	6.47	0.107
Treatment	27361	2	13680	0.62	0.581
Time x Treatment	252678	1	219713	1.26	0.379
(k) Nematoda					
Time	2894	2	1793	2.39	0.227
Treatment	**9313**	**2**	**4656**	**27.44**	**0.005**
Time x Treatment	7631	2	4301	2.82	0.184

Bold values indicate significant differences, $p < 0.05$. Refer to Figure 4.5 for control abbreviations.

4.3.2.1.7 Classification of high-shore controls and treatment communities

The community structure of the treatment and the controls of the high-shore were divided into four groups, one formed by the treatment and defaunated control communities from wk 4 and the treatment community at wk 6 (Figure 4.14). The second group indicated a similarity of all mudflat control communities for each sampling occasion except wk 2. The next group consisted of treatment and defaunated control communities from wks 8 to 17, followed by a final group of treatment and control communities taken at wk 2 and control communities at wk 6.

4.3.2.1.8 Tidal height comparisons of the upper- and high-shores - univariate community indices

The mean abundance of total individuals at the upper- and high-shores were significantly different between time x tidal height when comparing a repeated measures analysis of variance between controls 1 and 2 with the treatment between weeks at the upper-shore compared to the high-shore (Table 4.8). Also, the mean abundance of total individuals and the number of species at the upper- and high-shores were significantly different between treatment x tidal height when comparing a repeated measures analysis of variance between control 1 and treatment 1, followed by control 2 with treatment 1 when comparing the upper- and high-shore tidal heights (Table 4.8). Furthermore, repeated effects of the mean abundance of total individuals at the upper- and high-shore tidal heights exhibited a significant difference between time x treatment x tidal height. Significant repeated contrasts between time x tidal height revealed a difference of mean abundance of total individuals between wks 15 and 17 when comparing the upper- and high-shore colonization of the controls and treatment (Appendix 2 Table 4.8) a higher mean abundance of total individuals colonized the high-shore controls and treatment when compared to the upper-shore. Furthermore, a significant difference between the defaunated control and the treatment occurred when comparing tidal heights. Repeated contrasts of the number of species significantly differed between wks 4 to 6 and wks 10 to 15, also significant differences between treatment x tidal height occurred when comparing control 2 with treatment 1 at the upper- and high-shore.

Table 4.8: Repeated measures ANOVA of univariate indices at the upper- and high-shore Control 1, Control 2 & Treatment 1 2002.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time x Tidal height	230272	3	87450	8.43	**0.005**
Treatment x Tidal height	78074	2	39037	8.97	**0.009**
Time x Treatment x Tidal height	211701	3	77090	5.03	**0.021**
(b) Number of species					
Time x Tidal height	92	2	54	2.60	0.148
Treatment x Tidal height	56	2	28	5.53	**0.031**
Time x Treatment x Tidal height	111	3	42	1.74	0.220

Bold values indicate significant differences, $p < 0.05$. Refer to Figures 4.4 & 4.5 for control abbreviations.

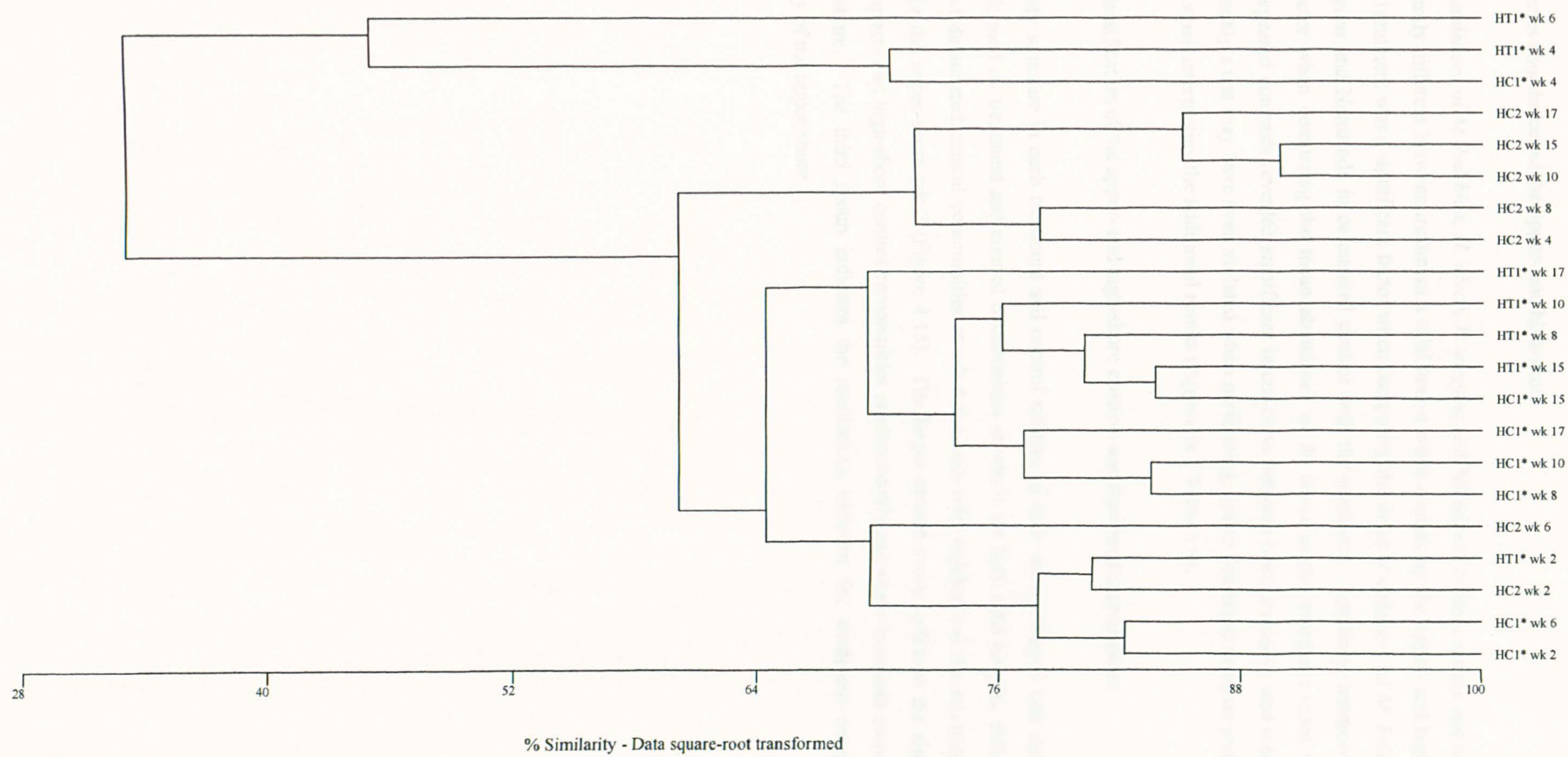


Figure 4.14: Assemblage composition similarity dendrogram of treatment type and sampling occasion at the high-shore, transect 1.

4.3.2.1.9 Species abundances of the upper- and high-shore

The mean abundances of *M. balthica, H. ulvae, P. elegans* and Nematoda in the controls and treatment were significantly different between treatment x tidal height when comparing the upper- and high-shores (Table 4.9). Treatment was a significant factor when comparing the mean abundances of *M. balthica, H. ulvae, P. elegans* and Nematoda in defaunated control with the treatment. Similarly, treatment was a significant factor when comparing the mean abundance of *H. ulvae* in the mudflat control with the treatment. Repeated contrasts revealed significant interactions between time, treatment and tidal height however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Table 4.9).

4.3.2.1.10 Classification of the upper- and high-shore controls and treatment communities

The community structure in each treatment and control relative to time were arranged into three main groups, one formed by treatment and control communities at wks 4 for both tidal heights, followed by treatments and defaunated control communities at wk 6 for both tidal heights and the mudflat control community for the upper-shore wk 2 (Figure 4.15). The larger second group indicates the similarities between the upper- and high-shore control communities predominantly and some treatment communities of the high-shore. The third group indicates the similarities between the treatment communities predominantly of the upper-shore.

Table 4.9: Repeated measures ANOVA of abundance data for common taxa at the upper- and high-shore Control 1, Control 2 & Treatment 1 2002.

Source	SS	DF	MS	F	P
(a) *A. tenuis*					
Time x Tidal height	286	1	220	2.78	0.154
Treatment x Tidal height	540	1	532	5.24	0.083
Time x Treatment Tidal height	791	1	600	3.65	0.108
(b) *M. balthica*					
Time x Tidal height	487	2	238	1.91	0.209
Treatment x Tidal height	**2524**	**2**	**1262**	**29.34**	**0.000**
Time x Treatment Tidal height	1249	2	568	2.57	0.129
(c) *H. ulvae*					
Time x Tidal height	1405	2	861	2.51	0.158
Treatment x Tidal height	**477**	**2**	**238**	**9.37**	**0.008**
Time x Treatment Tidal height	803	2	490	1.59	0.268
(d) *H. diversicolor*					
Time x Tidal height	135	2	70	1.16	0.362
Treatment x Tidal height	4	2	2	0.14	0.869
Time x Treatment Tidal height	348	2	211	1.20	0.346
(e) *H. diversicolor* j					
Time x Tidal height	3037	1	2862	1.46	0.294
Treatment x Tidal height	149	1	145	0.52	0.514
Time x Treatment Tidal height	2117	1	1787	1.62	0.271
(f) *M. aestuarina*					
Time x Tidal height	66	1	60	0.71	0.456
Treatment x Tidal height	27	1	27	0.99	0.376
Time x Treatment Tidal height	106	1	95	0.66	0.474
(g) *P. cornuta*					
Time x Tidal height	296	1	219	1.10	0.367
Treatment x Tidal height	0	1	0	0.00	0.974
Time x Treatment Tidal height	594	1	475	1.06	0.372
(h) *P. elegans*					
Time x Tidal height	161	2	71	1.41	0.297
Treatment x Tidal height	**145**	**2**	**72**	**6.26**	**0.023**
Time x Treatment Tidal height	253	2	116	1.07	0.391
(i) *S. shrubsolii*					
Time x Tidal height	221	2	103	1.53	0.271
Treatment x Tidal height	111	1	107	3.23	0.144
Time x Treatment Tidal height	643	2	296	2.05	0.186
(j) *T. benedii*					
Time x Tidal height	297093	1	239180	4.62	0.082
Treatment x Tidal height	19007	2	9503	0.82	0.475
Time x Treatment Tidal height	145832	1	115648	1.37	0.309
(k) Nematoda					
Time x Tidal height	1218	2	522	0.82	0.486
Treatment x Tidal height	**4369**	**2**	**2185**	**6.69**	**0.020**
Time x Treatment Tidal height	5020	3	1845	1.82	0.205

Bold values indicate significant differences, $p<0.05$. Refer to Figures 4.4 & 4.5 for control abbreviations.

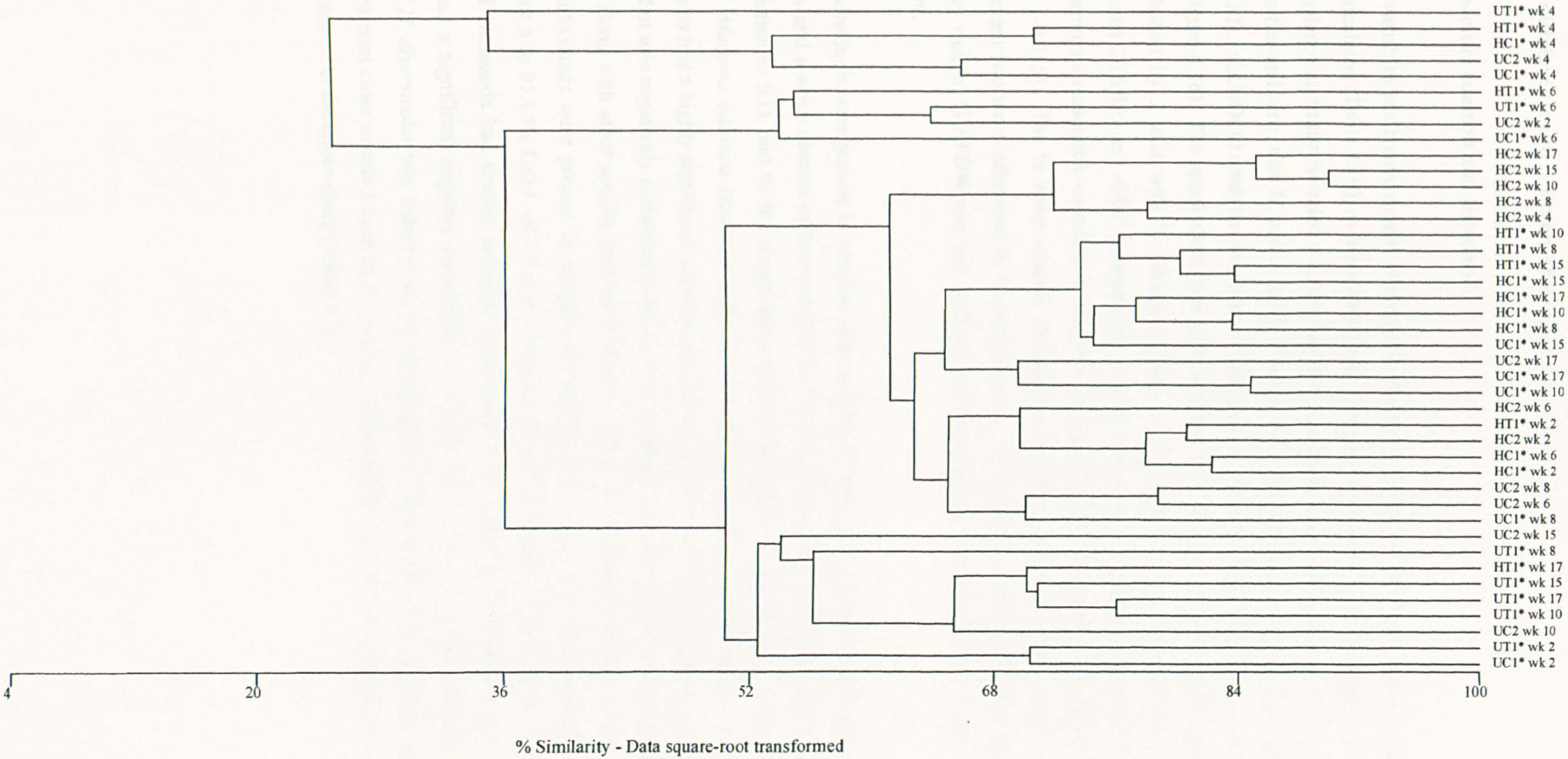


Figure 4.15: Similarity of treatment type and sampling occasion at the upper- and high-shores, transect 1.

4.3.3 Species distribution and sediment characteristics, transect 1

4.3.3.1 Upper-shore controls and treatment

The sediment variables preference ranges of the most abundant species in the upper-shore experimental blocks were calculated (Table 4.10), as were Spearman correlations (Table 4.11). Spearman correlations of species abundance and time revealed a highly significant positive correlation between *P. cornuta* and *T. benedii* densities and time, also *H. ulvae* and *P. elegans* showed a significant positive correlation with time (Table 4.12). CANOCO analysis linked any correlation between sediment parameters and species distribution (Figure 4.16). The upper-shore data indicated that 18.0 % of the variation in the species data could be explained by 2 axis with % silt/clay content and % sand content showing the strongest correlation to axis 2 (0.005 and -0.005 respectively) and skewness was correlated with axis 1 (-0.008). Other parameters with reasonable correlations with axis 2 included sediment % water content (0.015) and % dry weight (-0.015). The % water content of sediment influenced quadrant one species. Species present in quadrant two were influenced by % sand content. The species present in quadrant three were linked to % dry weight, % AFDW and S.D. and quadrant four species were linked to % L.O.I. and the silt/clay content.

Abra tenuis individuals were present in samples with an S.D. of 1.8 to 2.0, a % dry weight ranging from 45.8 to 59.1 % and a water content of between 33.0 to 41.0 % (Table 4.10). *A. tenuis* had a significant positive correlation to S.D. and % dry weight but a significant negative correlation to % water content (Table 4.11). *Macoma balthica* inhabited samples with similar sediment characteristics to *A. tenuis*. *Macoma balthica* had a highly significant positive correlation to S.D., a significant positive correlation to % dry weight but was negatively correlated to the % water content. *Macoma balthica* was linked with % water content along with other species such as *H. diversicolor* j. and Nematoda (Figure 4.16). *Hediste diversicolor* individuals were present in samples defined by a S.D. of 1.8 to 2.0, a silt/clay content ranging from 84.4 to 91.1 %, L.O.I. of 3.1 to 4.1 % and a water content of 33.0 to 41.0 %. *Streblospio shrubsolii* and Nematoda had similar sediment preferences to *H. diversicolor* (Table 4.10). *Hediste diversicolor* had a significant negative correlation to % L.O.I. (Table 4.11). CCA indicated that the distribution of *H. diversicolor* was linked to the % sand content (Figure 4.16). The skewness influenced those species present close to axis 1 such as *P. cornuta*. Only significant positive correlations of species interactions occurred at the upper-shore (Table 4.12).

Table 4.10: Arrangement of upper-shore transect 1 species according to sediment preferences.

Species	Ranges Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content
A. tenuis	5.90-6.48	1.77-2.01	-0.02-0.18	9.58-15.65	84.35-91.07	45.75-59.13	3.06-4.19	33-42
M. balthica	5.90-6.48	1.77-2.03	-0.02-0.18	9.28-15.65	84.35-90.72	45.61-59.13	3.06-4.19	33-42
Tellinacea j	5.95-6.48	1.77-2.01	-0.02-0.18	8.93-12.69	85.67-91.07	47.63-59.13	3.55-4.19	33-42
H. ulvae	5.90-6.48	1.77-2.03	-0.02-0.18	8.93-15.65	84.35-91.07	45.61-59.13	3.06-4.19	33-42
H. diversicolor	5.90-6.48	1.77-2.03	-0.02-0.18	8.93-15.65	84.35-91.07	45.61-58.38	3.06-4.10	33-42
H. diversicolor j	5.90-6.48	1.77-2.03	-0.02-0.18	8.93-15.65	84.35-91.07	45.61-58.38	3.06-4.10	33-42
M. aestuarina	5.95-6.46	1.77-2.03	-0.03-0.14	9.93-12.69	87.31-91.07	47.63-58.38	3.55-4.10	33-42
P. cornuta	5.90-6.45	1.83-1.96	-0.03-0.18	9.58-15.65	84.35-90.42	45.61-59.13	3.06-4.19	33-42
P. elegans	5.91-6.46	1.77-2.03	-0.03-0.14	8.93-14.33	85.67-91.07	45.61-59.13	3.31-4.19	33-42
S. shrubsolii	5.90-6.48	1.77-2.01	-0.03-0.18	9.28-15.65	84.35-90.72	45.61-59.13	3.06-4.19	33-42
T. benedii	5.90-6.48	1.77-2.03	-0.03-0.18	8.93-15.65	84.35-91.07	45.61-59.13	3.06-4.19	33-42
Nematoda	5.90-6.48	1.76-2.01	-0.02-0.18	8.93-15.65	84.35-91.07	45.61-59.13	3.06-4.19	33-42

Table 4.11: Significant correlations between upper-shore transect 1, mean abundances of individual species and sediment characteristics, using Spearman correlation coefficient.

Species	Sediment characteristics Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content
A. tenuis	ns	+	ns	ns	ns	+	ns	-
M. balthica	ns	++	ns	ns	ns	+	ns	-
Tellinacea j	ns	ns	ns	ns	ns	ns	ns	ns
H. ulvae	ns	+	ns	ns	ns	++	ns	--
H. diversicolor	ns	ns	ns	ns	ns	ns	-	ns
H. diversicolor j	ns	ns	ns	ns	ns	ns	ns	ns
M. aestuarina	ns	ns	ns	ns	ns	ns	ns	ns
P. cornuta	ns	ns	ns	ns	ns	ns	ns	ns
P. elegans	ns	ns	ns	ns	ns	ns	ns	ns
S. shrubsolii	ns	ns	ns	ns	ns	ns	ns	ns
T. benedii	ns	ns	ns	ns	ns	+	ns	ns
Nematoda	ns	ns	ns	ns	ns	ns	ns	ns

Table 4.12: Significant correlations between upper-shore transect 1; mean abundances of individual species and time, using Spearman correlation coefficient.

Species	Species, treatment and week												
	A. tenuis	*M. balthica*	*Tellinacea* j	*H. ulvae*	*H. diversicolor*	*H. diversicolor* j	*M. aestuarina*	*P. cornuta*	*P. elegans*	*S. shrubsolii*	*T. benedii*	Nematoda	Week
A. tenuis		++	ns	++	ns	ns	ns	++	ns	++	++	ns	ns
M. balthica	++		ns	+	ns	ns	+	+	ns	++	++	ns	ns
Tellinacea j	ns	ns		ns	ns	ns	ns	ns	+	ns	ns	+	ns
H. ulvae	++	+	ns		ns	ns	+	++	+	++	++	ns	+
H. diversicolor	ns	ns	ns	ns		+	+	+	ns	ns	+	ns	ns
H. diversicolor j	ns	ns	ns	ns	+		+	ns	ns	ns	ns	ns	ns
M. aestuarina	ns	+	ns	+	+	+		ns	++	++	+	++	ns
P. cornuta	++	+	ns	++	+	ns	ns		ns	++	++	ns	++
P. elegans	ns	ns	+	+	ns	ns	++	ns		++	++	+	+
S. shrubsolii	++	++	ns	++	ns	ns	++	++	++		++	ns	ns
T. benedii	++	++	ns	++	+	ns	+	++	++	++		ns	++
Nematoda	ns	ns	+	ns	ns	ns	++	ns	+	ns	ns		ns

Key

p - values		Significance
$p > 0.05$	ns	not significant
$0.01 < p < 0.05$	- or +	Significant negative or positive correlation
$0.001 < p < 0.01$	- - or + +	very significant negative or positive correlation

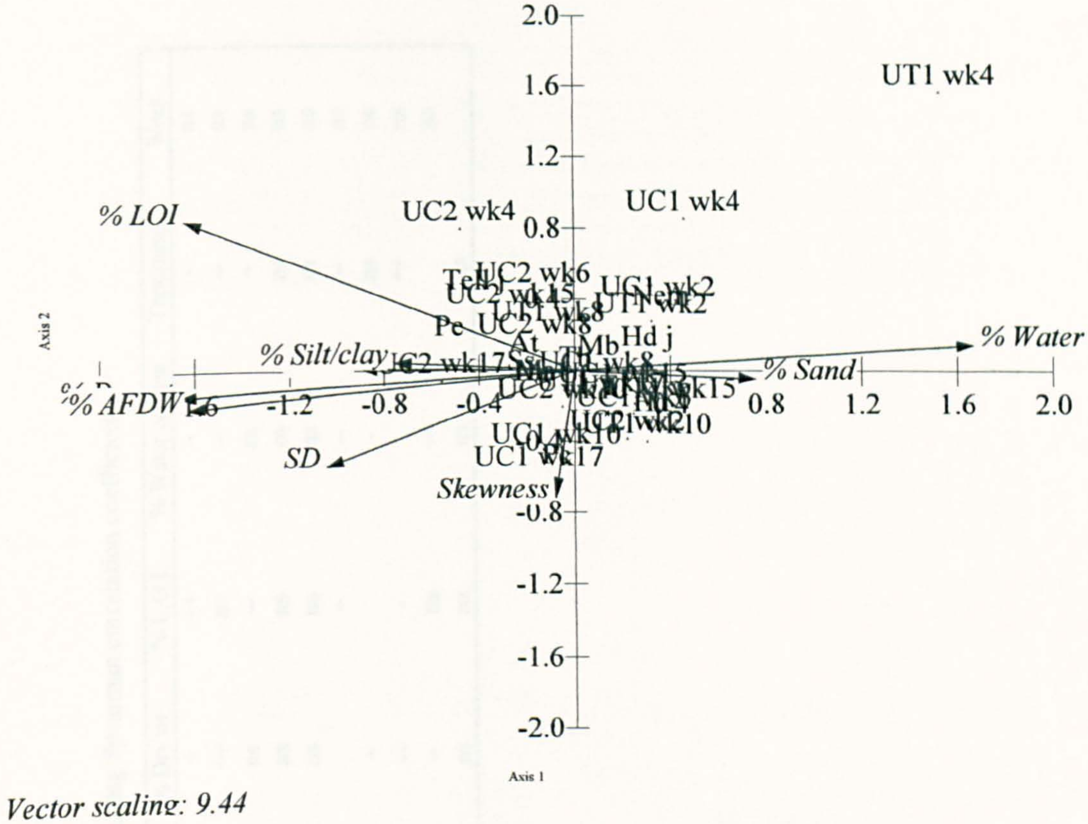


Figure 4.16: CCA of upper-shore transect 1 species distribution in relation to sediment characteristics on square-root transformed data.

Species key:

Abra tenuis (At)	*Macoma balthica* (Mb)	Tellinacea j (Tell j)
Hydrobia ulvae (Hu)	*Hediste diversicolor* (Hd)	*Hediste diversicolor* j (Hdj)
Manayunkia aestuarina (Ma)	*Polydora cornuta* (Pc)	*Pygospio elegans* (Pe)
Streblospio shrubsolii (Ss)	*Tubificoides benedii* (Tb)	Nematoda

Treatment type had a positive correlation to % water content, a negative correlation to S.D. and % dry weight the factor time was not significantly correlated (Table 4.13). The treatment data were divided into two groups, separated by an association towards water and sand contents (Figure 4.17), group one consisted of upper-shore treatments from wks 8 to 15 and contained a higher sand content of 12.7 to 15.7 % and water content of 33.0 to 41.0 % (Table 4.14). Group two contained a cluster of upper-shore treatments characterised by water content of 33.0 and 41.0 %. The treatment samples from wk 4 were associated with the water content, a sand content of 10.7 % and a lower silt/clay content of 89.3 % (Table 4.14). A decrease of water content occurred in the controls of groups three and four (Figure 4.17).

Table 4.13: Significant correlations between upper-shore transect 1 sediment characteristics, using Spearman correlation coefficient.

Sediment variables	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content	Treatment	Week
Inc. M.P.D. Ø		+	--	--	++	+	++	-	-	ns
Inc. S.D. Ø	+		ns	ns	ns	++	ns	--	--	ns
Inc. Skewness	--	ns		+	-	ns	--	ns	+	ns
% Sand content	--	ns	+		--	ns	ns	ns	ns	ns
% Silt/clay content	++	ns	-	--		ns	ns	ns	ns	ns
% Dry wt	+	++	ns	ns	ns		+	--	--	ns
% L.O.I.	++	ns	--	ns	ns	+		-	ns	ns
% Water content	-	--	ns	ns	ns	--	-		++	ns
Treatment	-	--	+	ns	ns	--	ns	++		ns
Week	ns	ns	ns	ns	ns	ns	ns	ns	ns	

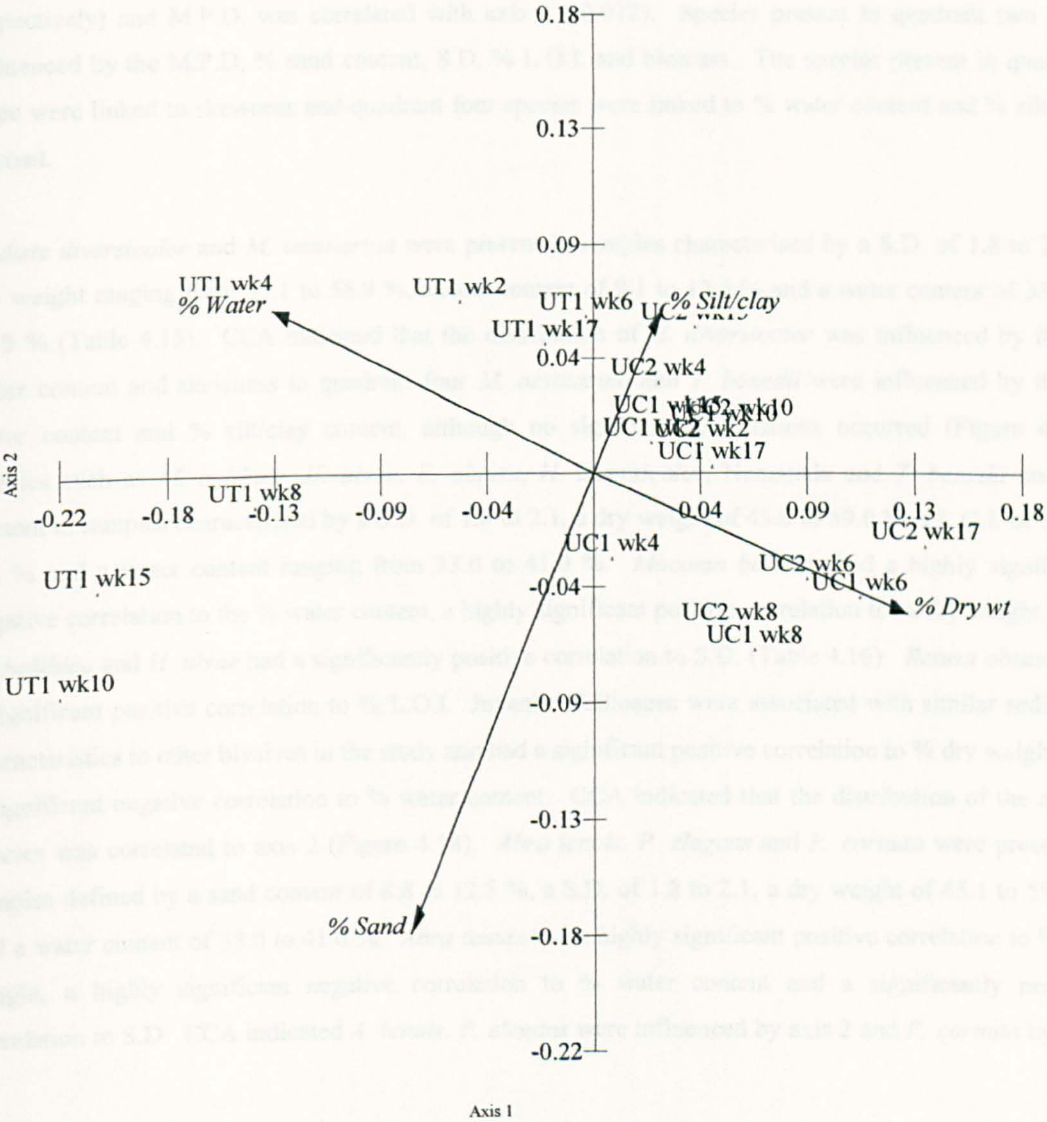
Key

p - values		Significance
p> 0.05	ns	not significant
0.01<p<0.05	- or +	Significant negative or positive correlation
0.001<p<0.01	- - or + +	very significant negative or positive correlation

Table 4.14: Analysis of upper-shore transect 1 groups sorted by PCA according to sediment characteristics.

Group	Site			Features
1	UT1 wk 8	UT1 wk 10	UT1 wk 15	Water content between 39 & 40%. Sand % between 12.69 & 15.65%.
2	UT1 wk 2 UT1 wk 17	UT1 wk 4	UT1 wk 6	Water content between 40 & 42%. Sand % between 9.28 & 10.67%. Silt/clay % between 89.33 & 90.72%
3	UC1 wk 2 UC1 wk 17 UC2 wk 8	UC1 wk 10 UC2 wk 2 UC2 wk 10	UC1 wk 15 UC2 wk 4 UC2 wk 15	Water content between 33 & 35%. Silt/clay % between 88.40 & 91.07%. Dry wt % between 53.61 & 56.58%.
4	UC1 wk 4 UC2 wk 6	UC1 wk 6 UC2 wk 17	UC1 wk 8	Dry wt % between 54.04 & 59.13%. Silt/clay % between 88.30 & 90.04%.

Refer to Figure 4.4 for control abbreviations.



Vector scaling: 0.20

Figure 4.17: PCA of the sediment characteristics of the upper-shore transect 1 treatment and controls on square-root transformed data. Refer to Figure 4.4 for control abbreviations.

4.3.3.2 High-shore controls and treatment

The sediment variables preference ranges of the most abundant species in the high-shore experimental blocks were calculated (Table 4.15), as were Spearman correlations (Table 4.16). Spearman correlations of species abundance and time revealed a highly significant positive correlation between *H. ulvae, H. diversicolor, P. cornuta* and *T. benedii* densities and time, also *H. diversicolor* j showed a significant positive correlation to time (Table 4.17). CANOCO analysis linked any correlation between sediment parameters and species distribution at the high-shore (Figure 4.18). The high-shore data indicated that 23.1 % of the variation in the species data could be explained by 2 axis with skewness, M.P.D. % silt/clay content and % sand content showing the strongest correlation to axis 1 (-0.018, 0.027, 0.035 and -0.035 respectively) and M.P.D. was correlated with axis 2 (-0.012). Species present in quadrant two were influenced by the M.P.D, % sand content, S.D. % L.O.I. and biomass. The species present in quadrant three were linked to skewness and quadrant four species were linked to % water content and % silt/clay content.

Hediste diversicolor and *M. aestuarina* were present in samples characterised by a S.D. of 1.8 to 2.1, a dry weight ranging from 45.1 to 58.9 %, a sand content of 9.1 to 12.5 % and a water content of 33.0 to 41.0 % (Table 4.15). CCA indicated that the distribution of *H. diversicolor* was influenced by the % water content and skewness in quadrant four *M. aestuarina* and *T. benedii* were influenced by the % water content and % silt/clay content, although no significant correlations occurred (Figure 4.18). Species such as *M. balthica, H. ulvae, R. obtusa, H. diversicolor*, Nematoda and *T. benedii* and are present in samples characterised by a S.D. of 1.8 to 2.1, a dry weight of 45.0 to 59.0 %, a L.O.I. of 3.2 to 4.2 % and a water content ranging from 33.0 to 41.0 %. *Macoma balthica* had a highly significant negative correlation to the % water content, a highly significant positive correlation to % dry weight, both *M. balthica* and *H. ulvae* had a significantly positive correlation to S.D. (Table 4.16). *Retusa obtusa* had a significant positive correlation to % L.O.I. Juvenile Tellinacea were associated with similar sediment characteristics to other bivalves in the study and had a significant positive correlation to % dry weight and a significant negative correlation to % water content. CCA indicated that the distribution of the above species was correlated to axis 2 (Figure 4.18). *Abra tenuis, P. elegans* and *P. cornuta* were present in samples defined by a sand content of 8.8 to 12.5 %, a S.D. of 1.8 to 2.1, a dry weight of 45.1 to 59.0 % and a water content of 33.0 to 41.0 %. *Abra tenuis* had a highly significant positive correlation to % dry weight, a highly significant negative correlation to % water content and a significantly positive correlation to S.D. CCA indicated *A. tenuis, P. elegans* were influenced by axis 2 and *P. cornuta* by axis 1.

Table 4.15: Arrangement of high-shore transect 1 species according to sediment preferences.

Species	Ranges							
	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content
A. tenuis	6.08-6.54	1.81-2.05	-0.01-0.14	8.85-12.46	87.54-91.16	45.06-58.94	3.35-4.19	33-42
M. balthica	6.08-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	44.96-58.94	3.15-4.19	33-42
Tellinacea j	6.17-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	45.54-58.94	3.15-4.19	33-42
H. ulvae	6.08-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	44.96-58.94	3.15-4.19	33-42
R. obtusa	6.08-6.54	1.81-2.05	-0.01-0.13	8.83-12.46	87.54-91.17	44.96-58.94	3.35-4.19	33-42
H. diversicolor	6.08-6.54	1.82-2.05	0.01-0.14	9.08-12.46	87.54-90.92	45.06-58.94	3.15-4.19	33-42
H. diversicolor j	6.08-6.54	1.82-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	45.06-58.94	3.15-4.19	33-42
M. aestuarina	6.08-6.54	1.81-2.05	0.01-0.13	9.08-12.46	87.54-90.92	45.06-58.94	3.35-4.19	33-42
P. cornuta	6.24-6.54	1.82-2.05	0.01-0.14	9.08-12.46	87.54-90.92	45.54-58.94	3.15-4.19	33-42
P. elegans	6.17-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	45.54-58.94	3.15-4.19	33-42
S. shrubsolii	6.08-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	45.54-58.94	3.15-4.19	33-42
T. benedii	6.08-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	45.54-58.94	3.15-4.19	33-42
Nematoda	6.08-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	44.96-58.94	3.15-4.19	33-42

Table 4.16: Significant correlations between high-shore transect 1 mean abundances of individual species and sediment characteristics, using Spearman correlation coefficient.

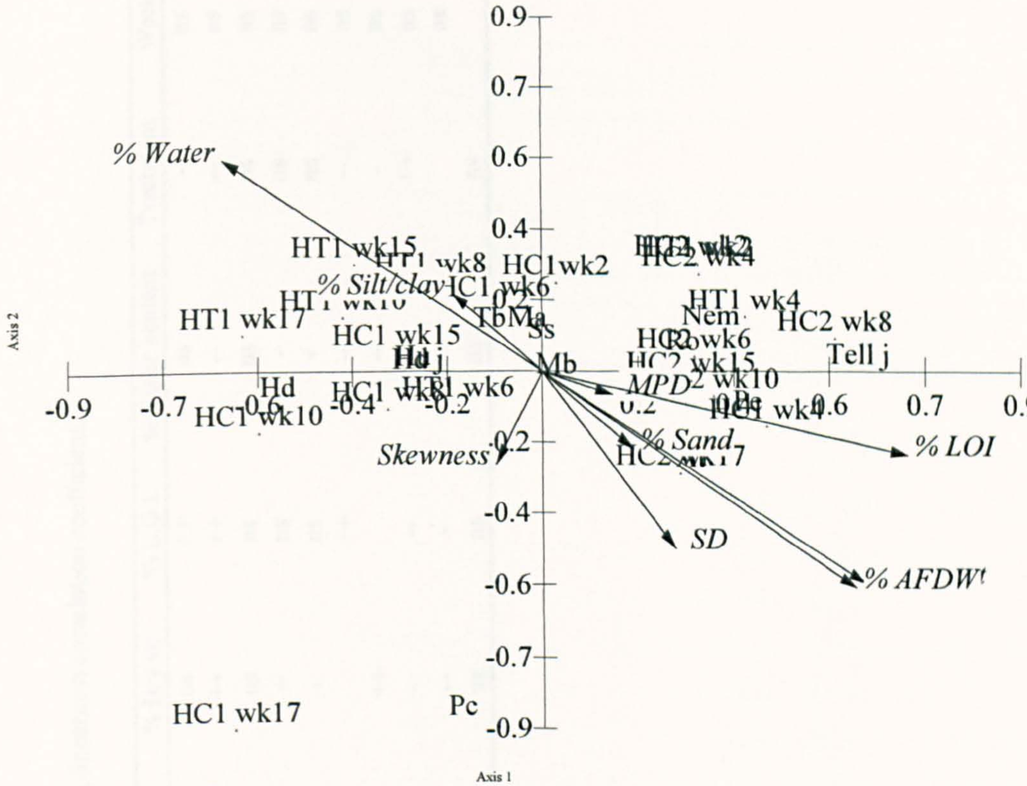
Species	Sediment characteristics							
	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content
A. tenuis	ns	+	ns	ns	ns	++	ns	--
M. balthica	ns	+	ns	ns	ns	++	ns	--
Tellinacea j	ns	ns	ns	ns	ns	+	ns	-
H. ulvae	ns	+	ns	ns	ns	ns	ns	ns
R. obtusa	ns	ns	ns	ns	ns	ns	+	ns
H. diversicolor	ns	ns	ns	ns	ns	ns	ns	ns
H. diversicolor j	ns	ns	ns	ns	ns	ns	ns	ns
M. aestuarina	ns	ns	ns	ns	ns	ns	ns	ns
P. cornuta	ns	ns	ns	ns	ns	ns	ns	ns
P. elegans	ns	ns	ns	ns	ns	ns	ns	ns
S. shrubsolii	ns	ns	ns	ns	ns	ns	ns	ns
T. benedii	ns	ns	ns	ns	ns	ns	ns	ns
Nematoda	ns	ns	ns	ns	ns	ns	ns	ns

Table 4.17: Significant correlations between high-shore transect 1 mean abundance of individual species and time, using Spearman correlation coefficient.

Species	Species, treatment and week													
	A. tenuis	*M. balthica*	*Tellinacea* j	*H. ulvae*	*R. obtusa*	*H. diversicolor*	*H. diversicolor* j	*M. aestuarina*	*P. cornuta*	*P. elegans*	*S. shrubsolii*	*T. benedii*	Nematoda	Week
A. tenuis		++	++	ns	+	ns	ns	ns	ns	+	ns	ns	ns	ns
M. balthica	++		++	ns	++	ns	ns	ns	ns	++	+	+	+	ns
Tellinacea j	++	++		ns	++	ns	ns	ns	ns	++	++	ns	++	ns
H. ulvae	ns	ns	ns		ns	+	ns	ns	+	ns	ns	ns	ns	++
R. obtusa	+	++	++	ns		ns	-	ns	ns	+	ns	ns	++	ns
H. diversicolor	ns	ns	ns	+	ns		++	+	++	ns	ns	++	ns	++
H. diversicolor j	ns	ns	ns	ns	-	++		ns	++	ns	ns	++	-	+
M. aestuarina	ns	ns	ns	ns	ns	+	ns		ns	ns	+	ns	ns	ns
P. cornuta	ns	ns	ns	+	ns	++	++	ns		ns	ns	++	ns	++
P. elegans	+	++	++	ns	+	ns	ns	ns	ns		++	+	++	ns
S. shrubsolii	ns	+	++	ns	ns	ns	ns	+	ns	++		++	+	ns
T. benedii	ns	+	ns	ns	ns	++	++	ns	++	+	++		ns	++
Nematoda	ns	+	++	ns	++	ns	-	ns	ns	++	+	ns		ns

Key

p - values		Significance
p> 0.05	ns	not significant
0.01<p<0.05	- or +	Significant negative or positive correlation
0.001<p<0.01	- - or + +	very significant negative or positive correlation



Vector scaling: 4.91

Figure 4.18: CCA of high-shore transect 1 species distribution in relation to sediment characteristics on square-root transformed data.

Species key:

Abra tenuis (At)	*Macoma balthica* (Mb)	Tellinacea j (Tell j)
Hydrobia ulvae (Hu)	*Retusa obtusa* (Ro)	*Hediste diversicolor* (Hd)
Hediste diversicolor j (Hdj)	*Manayunkia aestuarina* (Ma)	*Polydora cornuta* (Pc)
Pygospio elegans (Pe)	*Streblospio shrubsolii* (Ss)	*Tubificoides benedii* (Tb)
Nematoda		

Treatment type had a highly significant positive correlation to the % water content and a highly significant negative correlation to S.D. and % dry weight but a significant negative correlation to M.P.D. and % L.O.I., the factor time was not significantly correlated to any sediment parameter (Table 4.18). The high-shore treatment and controls were grouped into three clusters (Table 4.19). Groups one and two had a similar dry weight ranging from 53.8 to 58.6% and 53.8 to 55.1 % respectively, group one had a sand content of 9.9 to 11.4 % (Table 4.19). The mudflat high-shore control taken at wk 17 was separated from group one due to an elevated sand content of 12.5 % (Figure 4.19). Group three clusters included the high-shore treatment (Figure 4.19), characterised by increased water content of 33.0 to 41.0 % (Table 4.19). An outlier of the treatment taken at wk 15 was separated from group three due to a slightly higher sand content of 12.2 %.

Table 4.18: Significant correlations between high-shore transect 1 sediment characteristics, using Spearman correlation coefficient.

Sediment variables	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content	Treatment	Week
Inc. M.P.D. Ø		+	--	--	++	ns	++	ns	-	ns
Inc. S.D. Ø	+		ns	ns	ns	++	++	--	--	ns
Inc. Skewness	--	ns		++	--	ns	ns	ns	ns	ns
% Sand content	--	ns	++		--	+	ns	-	ns	ns
% Silt/clay content	++	ns	--	--		-	ns	+	ns	ns
% Dry wt	ns	++	ns	+	-		++	--	--	ns
% L.O.I.	++	++	ns	ns	ns	++		--	-	ns
% Water content	ns	--	ns	-	+	--	--		++	ns
Treatment	-	--	ns	ns	ns	--	-	++		ns
Week	ns	ns	ns	ns	ns	ns	ns	ns	ns	

Key

p - values		Significance
$p > 0.05$	ns	not significant
$0.01<p<0.05$	- or +	Significant negative or positive correlation
$0.001<p<0.01$	- - or + +	very significant negative or positive correlation

Table 4.19: Analysis of high-shore transect 1 groups sorted by PCA according to sediment characteristics.

Group	Site	Features
1	HC1 wk 4 HC1 wk 6 HC1 wk 8 HC1 wk 10 HC1 wk 17 HC2 wk 4 HC2 wk 6 HC2 wk 8 HC2 wk 10 HC2 wk 15	Sand % between 9.90 & 11.39%. Dry wt % between 53.78 & 58.61%.
2	HC1 wk 2 HC1 wk 15 HC2 wk 2 HC2 wk 15	Dry wt % between 54.03 & 55.09% Silt/clay % between 90.80 & 91.17%. LOI % between 3.85 & 4.01%.
3	HT1 wk 2 HT1 wk 4 HT1 wk 6 HT1 wk 8 HT1 wk 10 HT1 wk 17	Water content between 38 & 41%. Sand % between 9.80 & 10.60%. Silt/clay % between 89.40 & 90.20%.
Outlier	HT1 wk 15	Water content of 40%. Sand % of 12.23%.
Outlier	HC2 wk 17	Sand % of 12.46%. Dry wt % of 58.94%.

Refer to Figure 4.5 for control abbreviations.

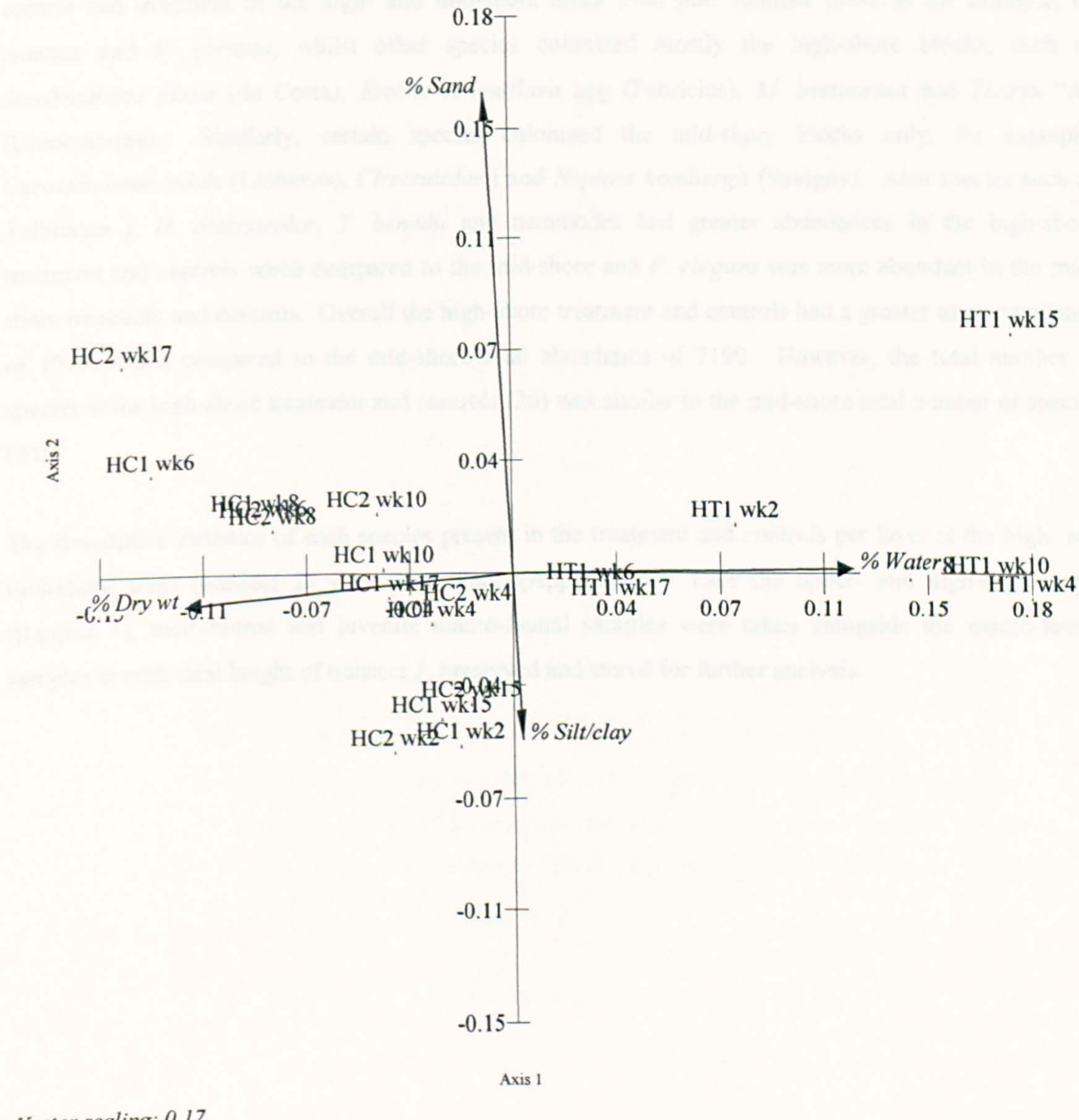


Figure 4.19: PCA of the sediment characteristics of the high-shore transect 1 treatment and controls on square-root transformed data. Refer to Figure 4.5 for control abbreviations.

4.3.4 Biota transect 2, 2002

4.3.4.1 High- and mid-shore

In total 22363 individuals were sampled from 31 taxa from all block types (Table 4.20). With 22, 19 and 18 taxa being sampled from the high-shore controls and treatment respectively and 13, 20 and 16 taxa being sampled from the mid-shore controls and treatment respectively. *Tubificoides benedii* had the greatest total dominance of 15118 throughout the blocks, followed by nemtodes (2229), *P. elegans* (1410) and *M. balthica* (1376) (Table 4.20). Species such as *M. balthica*, Tellinacea j, *H. ulvae*, *R. obtusa*, *H. diversicolor*, *P. elegans*, *S. shrubsolii*, *T. benedii* and nematodes were distributed throughout the controls and treatment at both the high- and mid-shores transect 2 and present at most sampling occasions and in high abundances. Other species were present in the established mudflat control towards the latter part of the experiment i.e. from mid- to late-summer, similarly certain species had colonized the defaunated control and treatment of the high- and mid-shore areas from mid summer onwards for example, *C. maenas* and *P. cornuta*, whilst other species colonized mostly the high-shore blocks, such as *Scrobicularia plana* (de Costa), *Eteone longa/flava* agg (Fabricius), *M. aestuarina* and *Tharyx* "A" (Unicomarine). Similarly, certain species colonized the mid-shore blocks only, for example, *Cerasterderma edule* (Linnaeus), *Cirratulidae* j and *Nephyts hombergii* (Savigny). Also species such as Tellinacea j, *H. diversicolor*, *T. benedii* and nematodes had greater abundances in the high-shore treatment and controls when compared to the mid-shore and *P. elegans* was more abundant in the mid-shore treatment and controls. Overall the high-shore treatment and controls had a greater total abundance of 15173 when compared to the mid-shore total abundance of 7190. However, the total number of species at the high-shore treatment and controls (26) was similar to the mid-shore total number of species (24).

The descriptive statistics of each species present in the treatment and controls per layer at the high- and mid-shore areas (transect 2) were determined (Appendices). Like the upper- and high-shore areas (transect 1), meio-faunal and juvenile macro-faunal samples were taken alongside the macro-faunal samples at each tidal height of transect 2, preserved and stored for further analysis.

Table 4.20: Taxa per treatment and control per sampling occasion at the high- and mid-shores, transect 2 2002 and the total number of individuals.

	HCA*	HCB	HTA*	H total	MC1*	MC2	MT1*	M total	Total (n)
Carcinus maenas		7	7	2	5-6			4	6
Carcinus maenas j		6		1				0	1
Megalopa	7	7		2				0	2
Crangon crangon	7			1				0	1
Corophium volutator	3			1		3	4-5	5	6
Corophium j	2		4	1		3		1	2
Cirrpedia			7	1				0	1
Cerasterderma edule				0		1-2, 4-5	2	9	9
Cerasterderma edule j				0		5		7	7
Abra tenuis	1, 3	2-7	1, 3	77	6	2-3, 5		10	87
Macoma balthica	1-7	1-7	1-7	904	1-6	1-6	1-6	472	1376
Scrobicularia plana	3	1, 3, 5-6		6			3	1	7
Tellinacea j	1-4, 6	1-7	1-3	510	2	1-5	3-4	49	559
Hydrobia ulvae	1-7	2-7	2-5	76	1-6	1-6	1-6	79	155
Retusa obtusa	1-3, 5, 7	1-7	1, 3, 5	113	1-5	1-6	1-3	169	282
Limpontia depressa	7	1-3, 6		23		1-3		34	57
Anatides mucosa				0		5		1	1
Cirratulidae j				0	3, 6	3	1	9	9
Eteone longa/flava agg	1-5	1-7	1-2, 6	106		1-5		20	126
Hediste diversicolor	1, 3-7	1, 4, 7	2-7	126	3, 5-6	3-6	4-6	31	157
Hediste diversicolor j	2-7	1-3, 5-7	1-7	314	1-6	1-2, 5	1, 3, 5-6	58	372
Manayunkia aestuarina	3-4	1-4, 6	1-3, 6	42				0	42
Nephyts hombergii				0	2-4	1-5	1-5	56	56
Phyllodocidae sp. Indet.				0		3		1	1
Polydora cornuta	4-5			3			5	2	5
Pygospio elegans	1-2, 4-5	1-7	1-3, 6	218	1-6	1-6	1-2, 4-5	1192	1410
Streblospio shrubsolii	2-4, 6	1-7	1-3, 5-6	108	1-5	1-5	1-2, 4-5	147	255
Tharyx "A"	3	2, 4, 6-7	5	10				1	11
Tubificoides benedii	1-7	1-7	1-7	10893	1-6	1-6	1-6	4225	15118
Enchytraeidae				0		4	2	2	2
Nemertea	6-7		7	5				0	5
Nematoda	1-6	1-7	1-7	1624	1-4	1-6	1-3, 5-6	605	2229
Insecta	5-6			2				0	2
Arachnid		4	3	2				0	2
Diptera larvae		3, 6		2				0	2
Total number of species	22	19	18	26	13	20	16	24	

1 indicates the presence in that treatment after 2 wks, 2=4 wks, 3=6 wks, 4=8 wks, 5=10 wks, 6=12 wks, (7=14 wks high-shore only). The total number of individuals sampled of each taxa throughout the experiment is given in the last column. * Disk present between mudflat surface and treatment deposition.

Note transect 2 high-shore control abbreviations: Defaunated control (HCA) and established mudflat control (HCB). Refer to Figure4.6 for mid-shore control abbreviations.

4.3.4.1.1 Univariate indices of the high-shore transect 2

The mean abundance of total individuals was greatest in the mudflat control each week (Figure 4.20 a). Colonization of the treatment reached a similar or higher levels to the defaunated control throughout the experiment at the high-shore transect 2. Overall the species richness was highest in the mudflat control and the species richness in the treatment cores was lower than the defaunated control cores on all occasions except wk 2 (Figure 4.20 b). Species diversity was similar in both the treatment and defaunated control cores but highest in the mudflat control (Figure 4.20 c). Pielou's evenness was higher in the treatment cores when compared to the defaunated control cores on all sampling occasions except wk 2, overall the mudflat control had the greatest evenness (Figure 4.20 d).

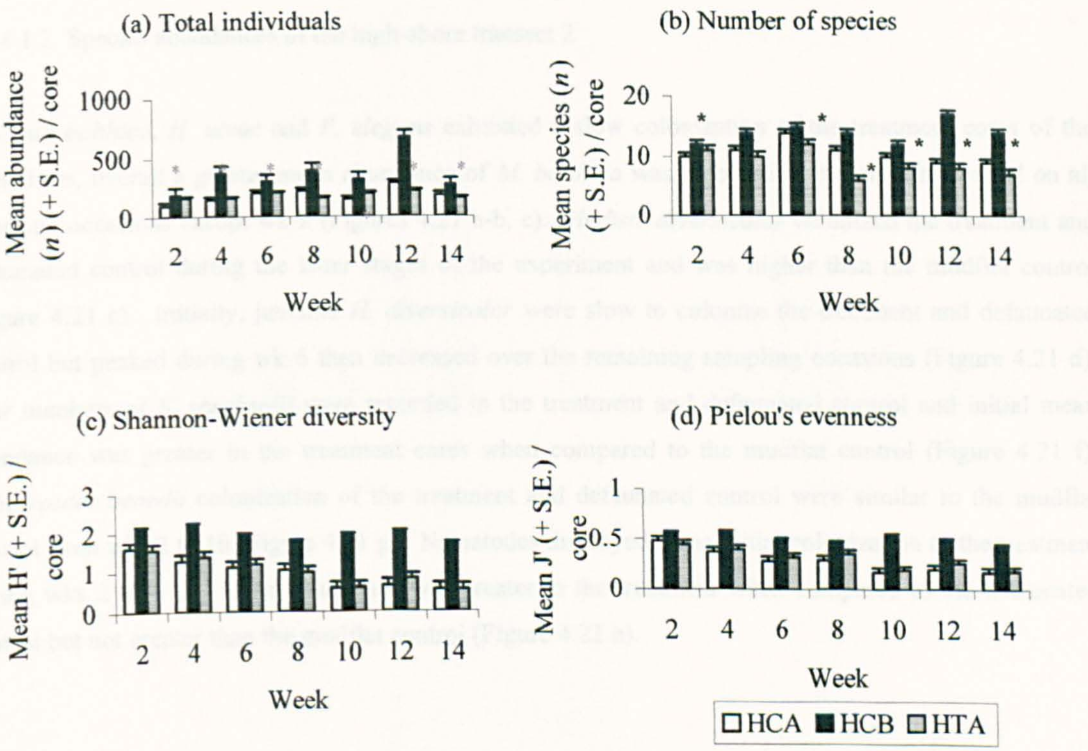


Figure 4.20 (a-d): Univariate parameters for each station at the high-shore transect 2 per core per sampling occasion (+ S.E., n=3). * Denotes a significant difference to the defaunated control or the * mudflat control. Refer to Table 4.20 for high-shore control abbreviations.

The mean abundance of total individuals and species richness at the high-shore transect 2 were significantly different between treatments when comparing a repeated measures analysis of variance between control 1 and treatment 1, followed by control 2 with treatment 1 (Table 4.21). Repeated contrasts revealed a significant difference of total individuals and species richness when comparing the controls with the treatment (Appendix 2 Table 4.21). Further repeated contrasts revealed significant interactions between time and treatment however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Table 4.21).

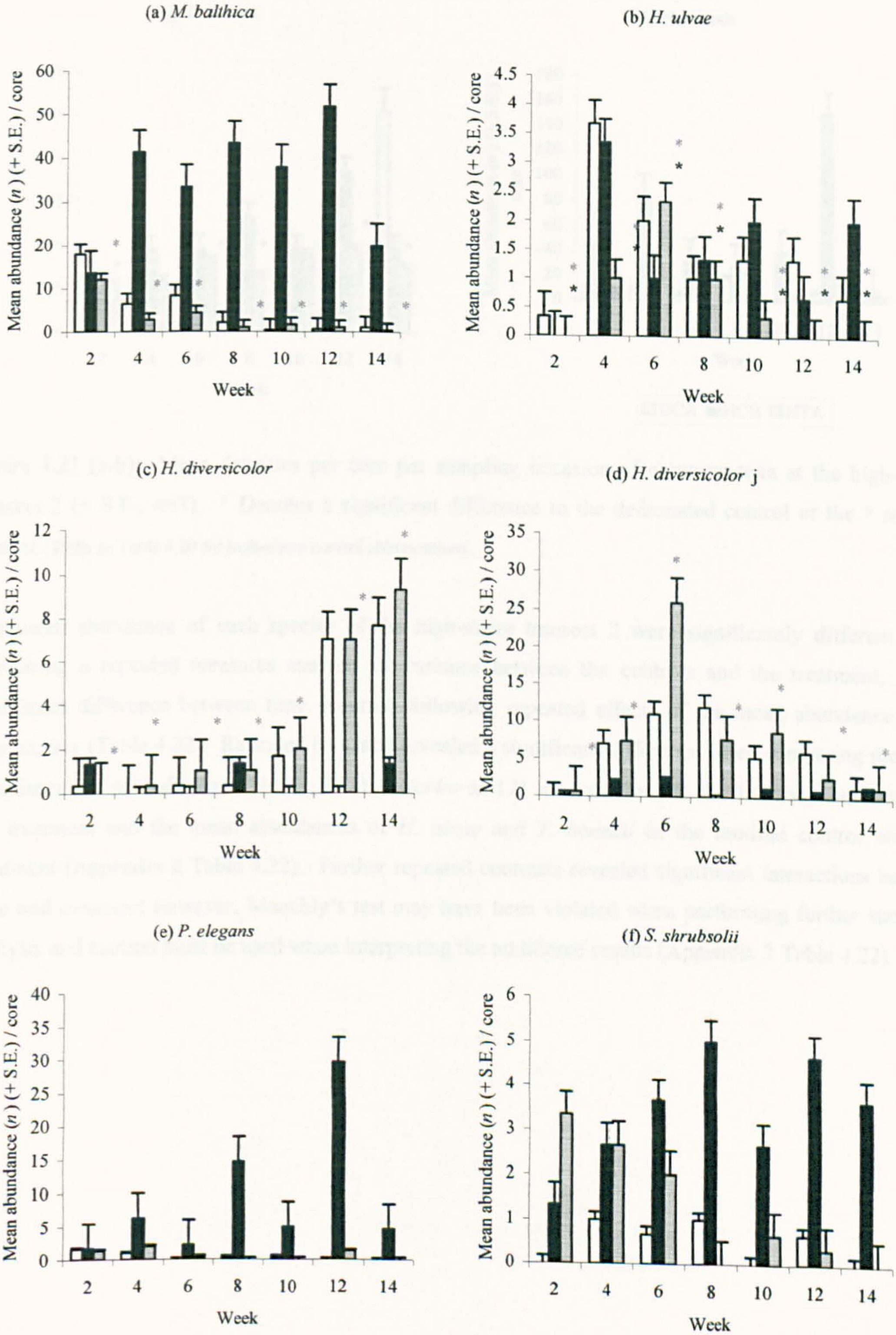
Table 4.21: Repeated measures ANOVA of univariate indices at the high-shore transect 2 Control 1, Control 2 and Treatment 1 2002.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time	285556	2	190048	3.74	0.152
Treatment	**421923**	**2**	**210962**	**31.15**	**0.004**
Time x Treatment	190406	1	140745	1.22	0.386
(b) Number of species					
Time	103	1	90	8.83	0.083
Treatment	**55**	**2**	**28**	**22.99**	**0.006**
Time x Treatment	97	1	68	2.28	0.246

Bold values indicate significant differences, $p<0.05$. Refer to Table 4.20 for high-shore control abbreviations.

4.3.4.1.2 Species abundances of the high-shore transect 2

Macoma balthica, H. ulvae and *P. elegans* exhibited a slow colonization of the treatment cores of the high-shore, overall a greater mean abundance of *M. balthica* was recorded in the mudflat control on all sampling occasions except wk 2 (Figures 4.21 a-b, e). *Hediste diversicolor* colonized the treatment and defaunated control during the latter stages of the experiment and was higher than the mudflat control (Figure 4.21 c). Initially, juvenile *H. diversicolor* were slow to colonize the treatment and defaunated control but peaked during wk 6 then decreased over the remaining sampling occasions (Figure 4.21 d). Low numbers of *S. shrubsolii* were recorded in the treatment and defaunated control and initial mean abundance was greater in the treatment cores when compared to the mudflat control (Figure 4.21 f). *Tubificoides benedii* colonization of the treatment and defaunated control were similar to the mudflat control from wks 2 to 10 (Figure 4.21 g). Nematodes displayed some initial colonization of the treatment during wks 2 to 4 and mean abundance was greater in the treatment when compared to the defaunated control but not greater than the mudflat control (Figure 4.21 h).


(a) M. balthica
(b) H. ulvae
(c) H. diversicolor
(d) H. diversicolor j
(e) P. elegans
(f) S. shrubsolii
Mean abundance (n) (+ S.E.) / core
Week
2 4 6 8 10 12 14

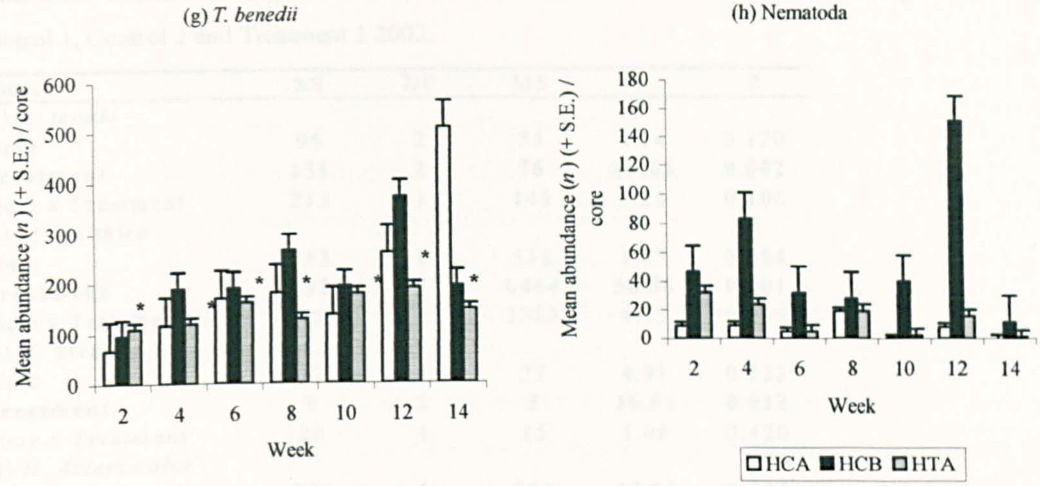


Figure 4.21 (a-h): Mean densities per core per sampling occasion of common taxa at the high-shore; transect 2 (+ S.E., n=3). * Denotes a significant difference to the defaunated control or the * mudflat control. Refer to Table 4.20 for high-shore control abbreviations.

The mean abundance of each species of the high-shore transect 2 were significantly different when comparing a repeated measures analysis of variance between the controls and the treatment, also a significant difference between time occurred following repeated effects of the mean abundance of *H. diversicolor* (Table 4.22). Repeated contrasts revealed a significant difference when comparing the mean abundances of *M. balthica*, *H. ulvae*, *H. diversicolor* and *H. diversicolor* j in the defaunated control with the treatment and the mean abundances of *H. ulvae* and *T. benedii* of the mudflat control with the treatment (Appendix 2 Table 4.22). Further repeated contrasts revealed significant interactions between time and treatment however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Table 4.22).

Table 4.22: Repeated measures ANOVA of abundance data for common taxa at the high-shore transect 2 Control 1, Control 2 and Treatment 1 2002.

Source	SS	DF	MS	F	P
(a) *A. tenuis*					
Time	96	2	55	4.14	0.120
Treatment	**151**	**2**	**76**	**49.63**	**0.002**
Time x Treatment	213	1	143	5.26	0.106
(b) *M. balthica*					
Time	653	1	511	1.23	0.384
Treatment	**12928**	**2**	**6464**	**56.86**	**0.001**
Time x Treatment	3659	2	2383	4.13	0.135
(c) *H. ulvae*					
Time	37	1	27	4.91	0.123
Treatment	**9**	**2**	**5**	**16.51**	**0.012**
Time x Treatment	20	1	15	1.06	0.420
(d) *H. diversicolor*					
Time	**305**	**1**	**211**	**17.52**	**0.025**
Treatment	**67**	**2**	**33**	**14.00**	**0.016**
Time x Treatment	151	2	90	6.24	0.075
(e) *H. diversicolor* j					
Time	965	1	918	6.45	0.121
Treatment	**506**	**2**	**253**	**20.63**	**0.008**
Time x Treatment	763	2	392	4.29	0.104
(f) *M. aestuarina*					
Time	19	1	15	1.55	0.334
Treatment	**26**	**2**	**13**	**27.30**	**0.005**
Time x Treatment	22	2	13	1.12	0.410
(g) *P. cornuta*					
Time	0	1	0	0.81	0.477
Treatment	0	2	0	3.00	0.160
Time x Treatment	1	1	1	0.81	0.477
(h) *P. elegans*					
Time	598	1	566	1.93	0.296
Treatment	**1035**	**2**	**517**	**16.39**	**0.012**
Time x Treatment	1219	1	1149	1.92	0.297
(i) *S. shrubsolii*					
Time	10	2	5	0.45	0.665
Treatment	**94**	**2**	**47**	**32.38**	**0.003**
Time x Treatment	55	2	29	1.19	0.394
(j) *T. benedii*					
Time	166492	2	89900	3.76	0.129
Treatment	**54027**	**2**	**27013**	**19.78**	**0.008**
Time x Treatment	48153	1	35762	0.57	0.561
(k) Nematoda					
Time	14960	2	9861	3.13	0.181
Treatment	**26725**	**2**	**13362**	**11.76**	**0.021**
Time x Treatment	20486	1	14816	2.51	0.230

Bold values indicate significant differences, $p<0.05$. Refer to Table 4.20 for high-shore control abbreviations.

4.3.4.1.3 Biomass of the high-shore community transect 2

Initially, the defaunated control had the highest mean wet weight biomass of *M. balthica* and the mudflat control was highest between wks 8 to 14, also the mudflat control had the greatest total biomass of *M. balthica* (10.1 g) followed by the defaunated control (2.0 g) and the treatment (0.8 g) (Figure 4.22 a). The treatment had the highest mean wet weight biomass of *H. diversicolor* on all sampling occasions except wk 8, also the defaunated control had a higher biomass than the mudflat control between wks 10 to 14, overall the treatment had the highest total biomass of *H. diversicolor* (1.0 g) after seven sampling occasions over fourteen weeks when compared to the defaunated control (0.4 g) and the mudflat control (0.2 g) (Figure 4.22 b). The mean wet weight biomass of *H. diversicolor* j was highest in the treatment during wks 2, 6 and 10 and the defaunated control was greatest on all other occasions and both the treatment and the defaunated control had the highest total biomass of *H. diversicolor* j (0.03 g), the mudflat control was less (0.002 g) (Figure 4.22 c). The treatment had the greatest mean wet weight biomass of *T. benedii* between wks 2 to 6 and at wk 10, the defaunated control was highest at wk 14, the treatment and both the controls had a total biomass of *T. benedii* of 0.5 g (Figure 4.22 d). The mean wet weight biomass of nematodes was greatest in the treatment at wk 8. However, the mudflat control was highest on all other sampling occasions and had the highest total biomass of nematodes (0.02 g) at the end of fourteen weeks, followed by the treatment (0.003 g) and the defaunated control (0.001 g) (Figure 4.22 e). Overall, *M. balthica* had the highest total biomass of 12.8 g after seven sampling occasions over fourteen weeks, followed by *H. diversicolor* (1.6 g), *T. benedii* (1.5 g), *H. diversicolor* j (0.05 g) and lastly, nematodes (0.03 g).

The mean AFDW biomass of *M. balthica* and *H. diversicolor* j followed a similar trend to the mean abundance between wks 2 to 14 (Figures 4.23 a, c). The mean AFDW biomass of *H. diversicolor* followed a similar trend to the mean abundances of the controls and treatment between wks 2 to 10 but differed from wks 12 to 14 (Figure 4.23 b). At wk 12 the AFDW biomass of the treatment was greater than the defaunated control and the AFDW biomass of the defaunated control equalled the mudflat control when compared to the mean abundance trends. Similarly, the mean AFDW biomass of *T. benedii* differed at wks 10 and 14 when compared to the mean abundances and a higher AFDW biomass occurred in the treatment when compared to the controls at wk 10. By wk 14 the AFDW of the controls and treatment were equal (Figure 4.23 d). The mean AFDW biomass of nematodes differed to the mean abundances at wks 4 and 8 when a greater AFDW biomass occurred in the treatment, at wk 6 the treatment biomass equalled the mean AFDW biomass of the mudflat control (Figure 4.23 e).

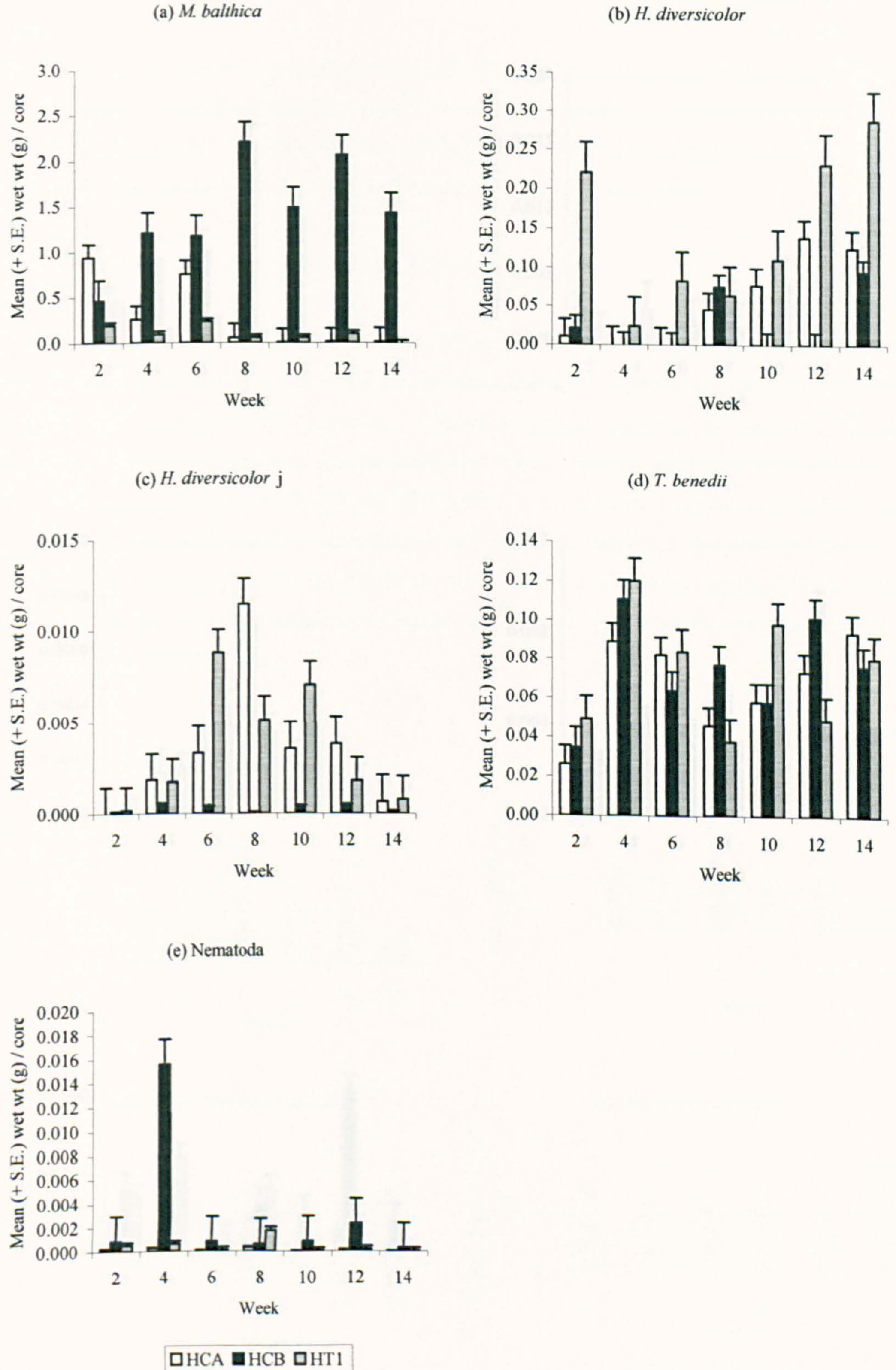


Figure 4.22 (a-e): Mean wet weight biomasses per core per sampling occasion of common taxa at the high-shore transect 2 (+ S.E., n=3). Refer to Table 4.20 for high-shore control abbreviations.

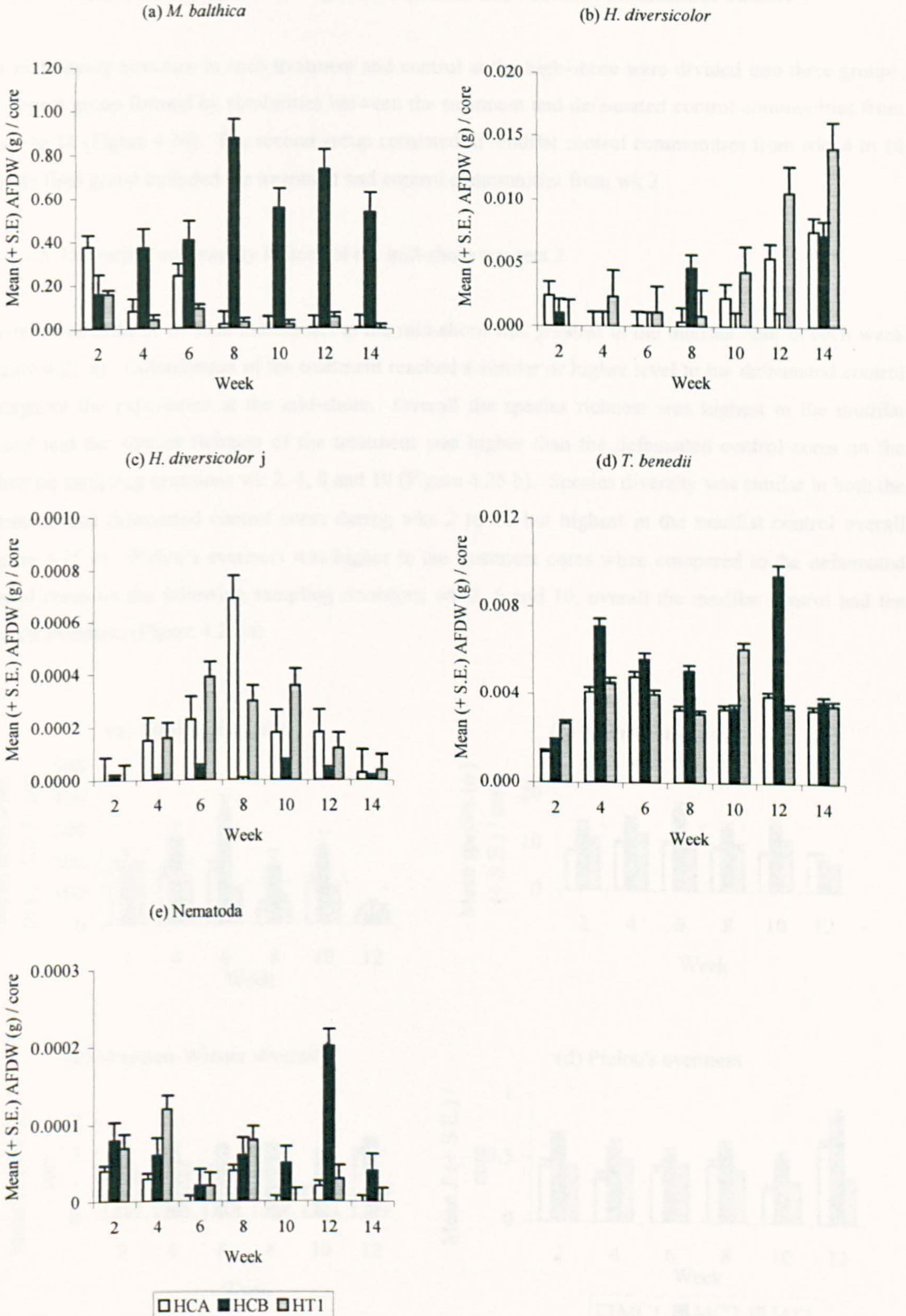


Figure 4.23 (a-e): Mean ash-free dry weight biomasses per core per sampling occasion of common taxa at the high-shore transect 2 (+ S.E., n=3). Refer to Table 4.20 for high-shore control abbreviations.

4.3.4.1.4 Classification results of the high-shore controls and treatment communities transect 2

The community structure in each treatment and control at the high-shore were divided into three groups, the largest group formed by similarities between the treatment and defaunated control communities from wks 4 to 14 (Figure 4.24). The second group consisted of mudflat control communities from wks 4 to 14 and the final group included the treatment and control communities from wk 2.

4.3.4.1.5 Univariate community indices of the mid-shore transect 2

The mean abundance of total individuals at the mid-shore was greatest in the mudflat control each week (Figure 4.25 a). Colonization of the treatment reached a similar or higher level to the defaunated control throughout the experiment at the mid-shore. Overall the species richness was highest in the mudflat control and the species richness of the treatment was higher than the defaunated control cores on the following sampling occasions wk 2, 4, 8 and 10 (Figure 4.25 b). Species diversity was similar in both the treatment and defaunated control cores during wks 2 to 10 but highest in the mudflat control overall (Figure 4.25 c). Pielou's evenness was higher in the treatment cores when compared to the defaunated control cores on the following sampling occasions wk 2, 6 and 10, overall the mudflat control had the greatest evenness (Figure 4.25 d).

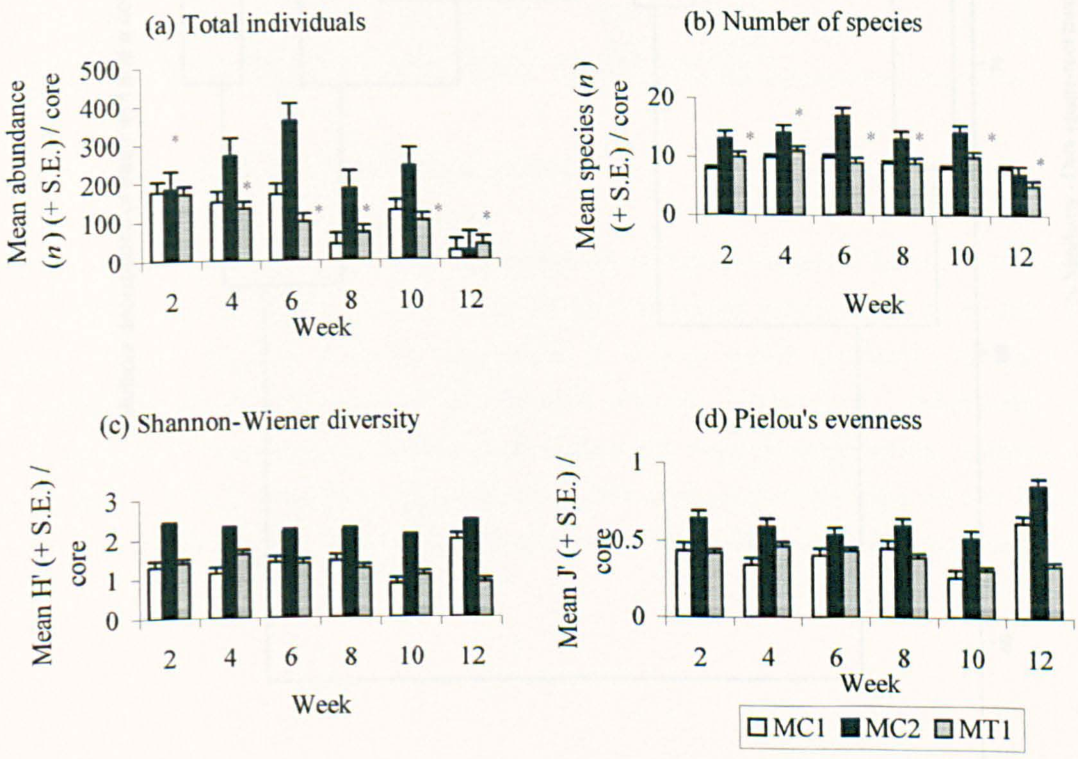


Figure 4.25 (a-d): Univariate parameters for each station at the mid-shore transect 2 per core per sampling occasion (+ S.E., n=3). * Denotes a significant difference to the defaunated control or the * mudflat control. Refer to Figure 4.6 for mid-shore control abbreviations.

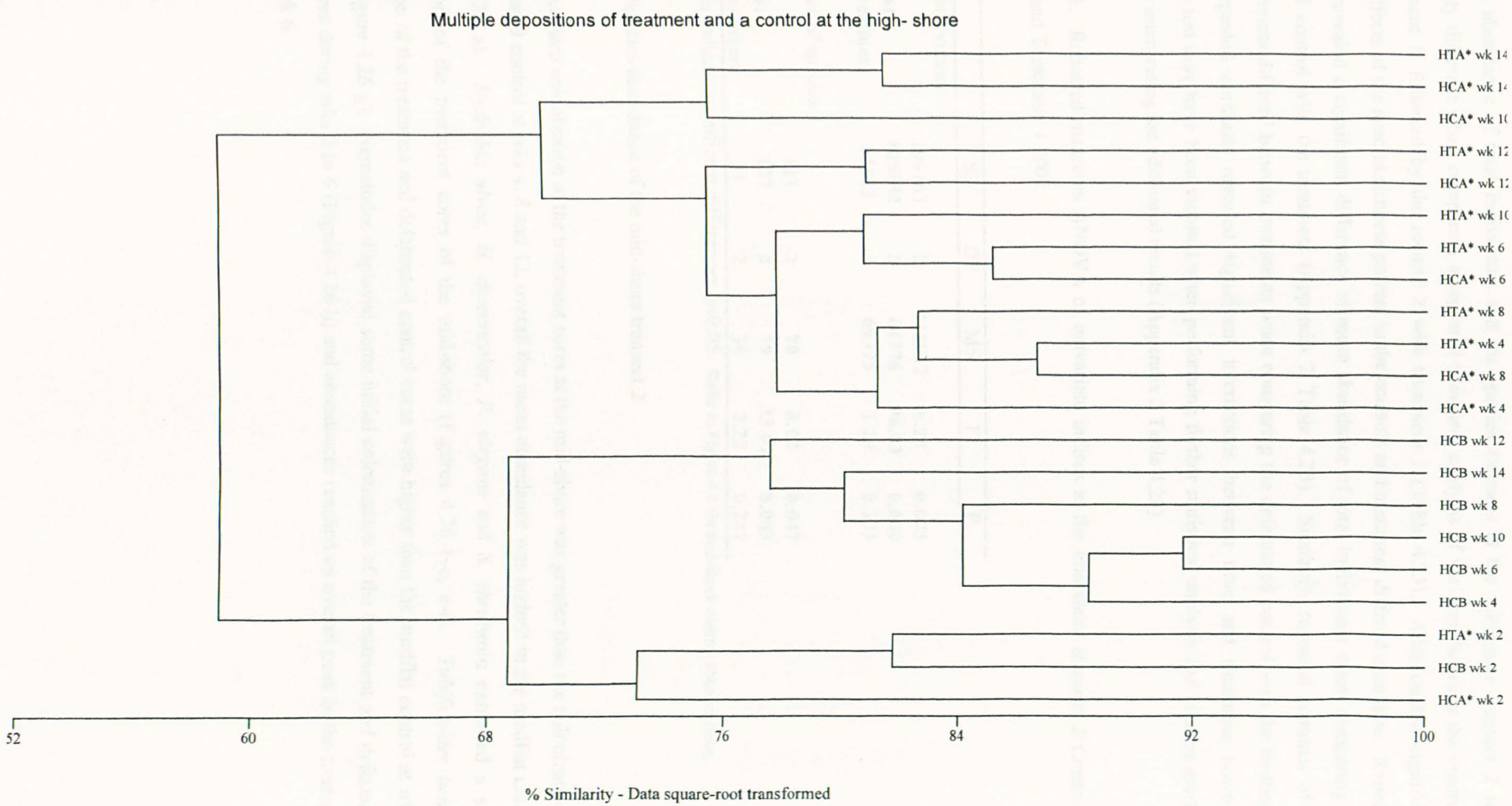


Figure 4.24: Assemblage composition similarity dendrogram of treatment type and sampling occasion at the high-shore, transect 2.

The mean abundance of total individuals and the species richness at the mid-shore transect 2 were significantly different when comparing a repeated measures analysis of variance between the control 1 and treatment 1, followed by the control 2 with treatment 1 (Table 4.23). Additionally, significant repeated effects of the species richness present in the controls and treatment differed over time. Repeated contrasts revealed a significant difference of mean abundance of total individuals when comparing the defaunated control with the treatment (Appendix 2 Table 4.23). Similarly, repeated contrasts of the species richness differed between treatments when comparing the defaunated control with the treatment. Further repeated contrasts revealed significant interactions between time and treatment however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Table 4.23).

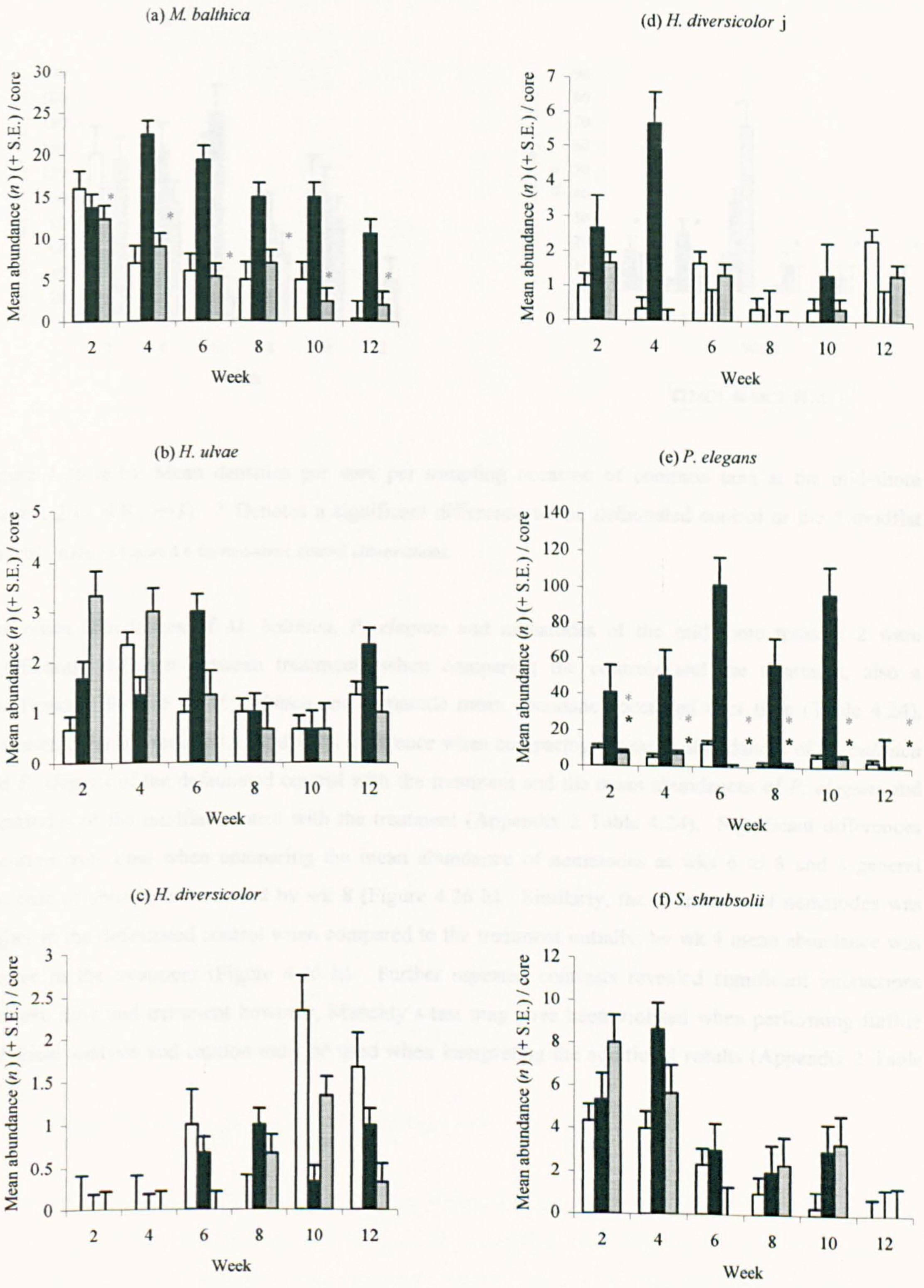
Table 4.23: Repeated measures ANOVA of univariate indices at the mid-shore transect 2 Control 1, Control 2 and Treatment 1 2002.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time	199163	2	118012	6.24	0.075
Treatment	**129552**	**2**	**64776**	**96.03**	**0.000**
Time x Treatment	85922	1	69375	1.29	0.373
(b) Number of species					
Time	**121**	**2**	**70**	**8.62**	**0.047**
Treatment	**157**	**2**	**79**	**33.09**	**0.003**
Time x Treatment	55	2	36	2.22	0.247

Bold values indicate significant differences, $p<0.05$. Refer to Figure 4.6 for mid-shore control abbreviations.

4.3.4.1.6 Species abundance of the mid-shore transect 2

Macoma balthica colonization of the treatment cores at the mid-shore was greater than the colonization of the defaunated control at wks 4, 8 and 12, overall the mean abundance was highest in the mudflat control (Figure 4.26 a). *Hydrobia ulvae, H. diversicolor, P. elegans* and *S. shrubsolii* exhibited a slow colonization of the treatment cores of the mid-shore (Figures 4.26 b-c, e-f). *Tubificoides benedii* colonization of the treatment and defaunated control cores were higher than the mudflat control at wks 2 and 12 (Figure 4.26 g). Nematodes displayed some initial colonization of the treatment and defaunated control cores during wks 2 to 6 (Figure 4.26 h) and abundances reached an overall peak in the treatment cores by wk 6.


(a) M. balthica
Mean abundance (n) (+ S.E.) / core
Week
(d) H. diversicolor j
Mean abundance (n) (+ S.E.) / core
Week
(b) H. ulvae
Mean abundance (n) (+ S.E.) / core
Week
(e) P. elegans
Mean abundance (n) (+ S.E.) / core
Week
(c) H. diversicolor
Mean abundance (n) (+ S.E.) / core
Week
(f) S. shrubsolii
Mean abundance (n) (+ S.E.) / core
Week

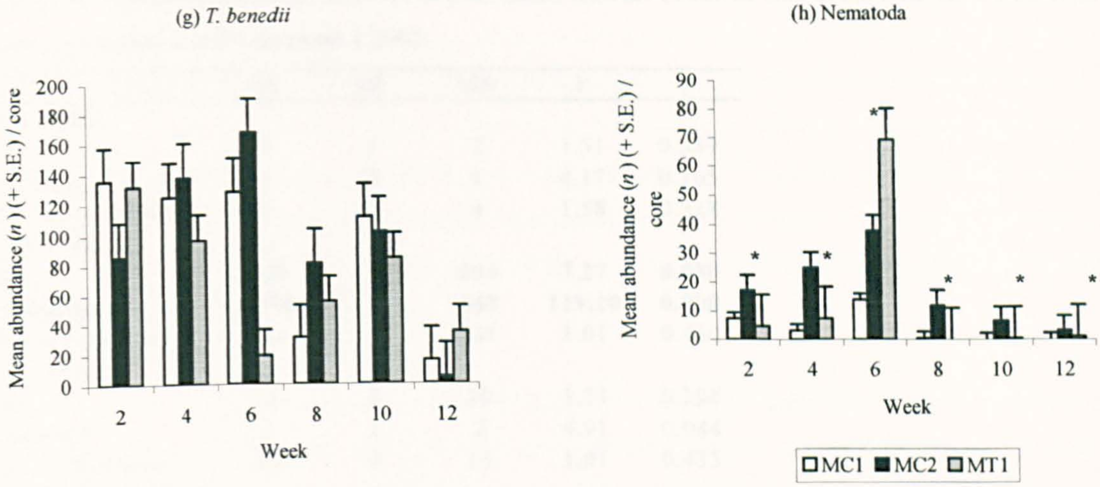


Figure 4.26 (a-h): Mean densities per core per sampling occasion of common taxa at the mid-shore transect 2 (+ S.E., n=3). * Denotes a significant difference to the defaunated control or the * mudflat control. Refer to Figure 4.6 for mid-shore control abbreviations.

The mean abundances of *M. balthica*, *P. elegans* and nematodes of the mid-shore transect 2 were significantly different between treatments when comparing the controls and the treatment, also a significant difference of *M. balthica* and nematode mean abundance occurred over time (Table 4.24). Repeated contrasts revealed a significant difference when comparing the mean abundances of *M. balthica* and *P. elegans* of the defaunated control with the treatment and the mean abundances of *P. elegans* and nematodes of the mudflat control with the treatment (Appendix 2 Table 4.24). Significant differences occurred over time when comparing the mean abundance of nematodes at wks 6 to 8 and a general decrease of abundance occurred by wk 8 (Figure 4.26 h). Similarly, the abundance of nematodes was higher in the defaunated control when compared to the treatment initially; by wk 4 mean abundance was greater in the treatment (Figure 4.26 h). Further repeated contrasts revealed significant interactions between time and treatment however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Table 4.24).

Table 4.24: Repeated measures ANOVA of abundance data for common taxa at the mid-shore transect 2 Control 1, Control 2 and Treatment 1 2002.

Source	SS	DF	MS	F	P
(a) *A. tenuis*					
Time	2	1	2	1.51	0.339
Treatment	3	2	1	4.17	0.105
Time x Treatment	5	1	4	1.58	0.328
(b) *M. balthica*					
Time	**563**	**2**	**294**	**7.27**	**0.050**
Treatment	**1096**	**2**	**548**	**119.10**	**0.000**
Time x Treatment	336	1	246	1.01	0.430
(c) *H. ulvae*					
Time	16	2	10	1.73	0.298
Treatment	3	2	2	4.91	0.084
Time x Treatment	22	2	13	1.01	0.435
(d) *H. diversicolor*					
Time	7	2	5	0.85	0.478
Treatment	6	1	6	8.14	0.104
Time x Treatment	11	2	6	1.11	0.413
(e) *H. diversicolor* j					
Time	22	2	11	0.85	0.490
Treatment	7	2	3	1.90	0.264
Time x Treatment	73	2	43	2.70	0.196
(f) *P. elegans*					
Time	8023	1	7810	1.10	0.406
Treatment	**33631**	**2**	**16815**	**104.14**	**0.000**
Time x Treatment	13360	1	13145	1.05	0.414
(g) *S. shrubsolii*					
Time	275	2	179	8.32	0.059
Treatment	27	2	13	2.57	0.191
Time x Treatment	62	2	32	0.70	0.544
(h) *T. benedii*					
Time	73283	1	56231	8.15	0.076
Treatment	6894	1	6606	6.04	0.129
Time x Treatment	42308	2	22283	2.02	0.251
(i) Nematoda					
Time	**9763**	**1**	**6985**	**20.93**	**0.022**
Treatment	**1609**	**2**	**805**	**13.45**	**0.017**
Time x Treatment	4463	1	3288	5.75	0.106

Bold values indicate significant differences, $p<0.05$. Refer to Figure 4.6 for mid-shore control abbreviations.

4.3.4.1.7 Biomass of the mid-shore community transect 2

Initially, the treatment had the highest mean wet weight biomass of *M. balthica*. However, the mudflat control was greatest between wks 4 to 12 and had the highest total biomass (3.5 g) after 6 sampling occasions over 12 weeks, when compared to the treatment (2.1 g) and the defaunated control (0.9 g) (Figure 4.27 a). The initial mean wet weight biomass of *H. diversicolor* was low but increased from wks 6 to 12 and the treatment had the highest biomass at wk 10, by wk 12 the defaunated control was greatest (Figure 4.27 b). The controls had the highest total mean wet weight biomass of *H. diversicolor* (0.1 g) overall followed by the treatment (0.04 g). The mudflat control had the highest mean wet weight biomass of *H. diversicolor* j at wk 2, by wk 4 the treatment was highest and the defaunated control was greatest at wks 6, 8 and 12 (Figure 4.27 c). The defaunated control had the highest total biomass of *H. diversicolor* j (0.002 g), although the treatment and the mudflat control had the same biomass (0.001 g). The defaunated control had the highest mean wet weight biomass of *T. benedii* at wks 2, 4 and 10, by wk 12 the treatment was highest and the controls and treatment had a total biomass of *T. benedii* of 0.2 g (Figure 4.27 d). The mean wet weight biomass of Nematoda was greatest in the mudflat control on all sampling occasions except wk 12 when the treatment had the highest biomass and had the greatest total mean biomass of Nematoda (0.003 g) followed by the mudflat control (0.002 g) and the defaunated control (0.001 g) (Figure 4.27 e). Overall, *M. balthica* had the highest total biomass (6.4 g) after 6 sampling occasions over 12 weeks followed by *T. benedii* (0.6 g), *H. diversicolor* (0.2 g), Nematoda (0.005 g) and *H. diversicolor* j (0.005 g).

The mean AFDW biomass of *M. balthica* followed a similar trend to the mean abundance from wks 4 to 14; initially the AFDW biomass was highest in the treatment and not the controls unlike the mean abundance at wk 2 (Figure 4.28 a). *Hediste diversicolor* mean AFDW biomass had a similar trend to the mean abundance each week apart from wks 6 and 12 when the AFDW biomass was greatest in the mudflat control (Figure 4.28 b). The mean AFDW biomass of *T. benedii* followed a similar trend to the mean abundances of the controls and treatment each week (Figure 4.28 c). However, Nematoda mean AFDW biomass differed to the mean abundances at wk 2 when the AFDW biomass was higher in the defaunated control when compared to the mudflat control and at wk 6 when the treatment had the lowest mean AFDW biomass and the mudflat control the greatest (Figure 4.28 d).

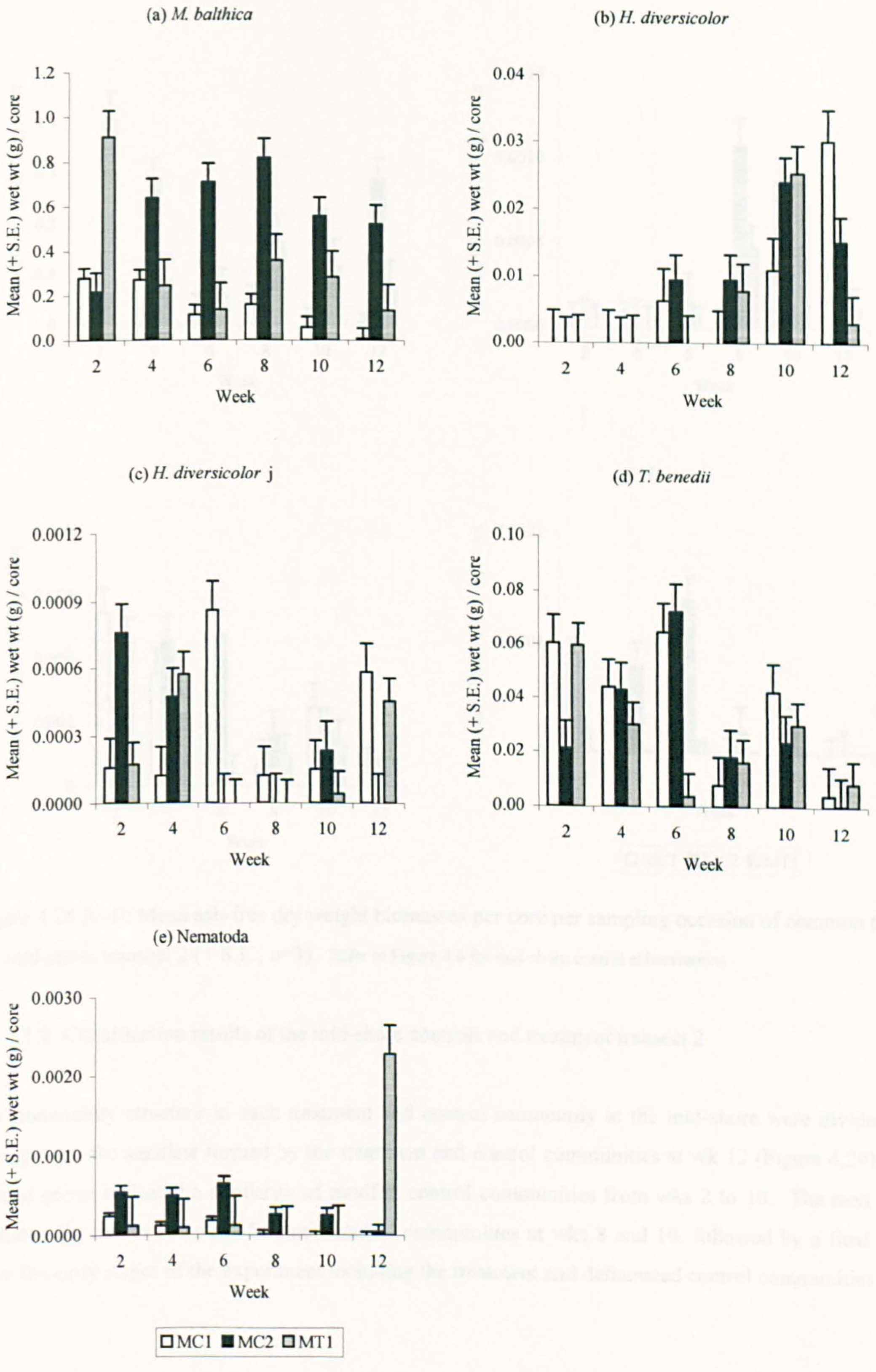


Figure 4.27 (a-e): Mean wet weight biomasses per core per sampling occasion of common taxa at the mid-shore transect 2 (+ S.E., *n*=3). Refer to Figure 4.6 for mid-shore control abbreviations.

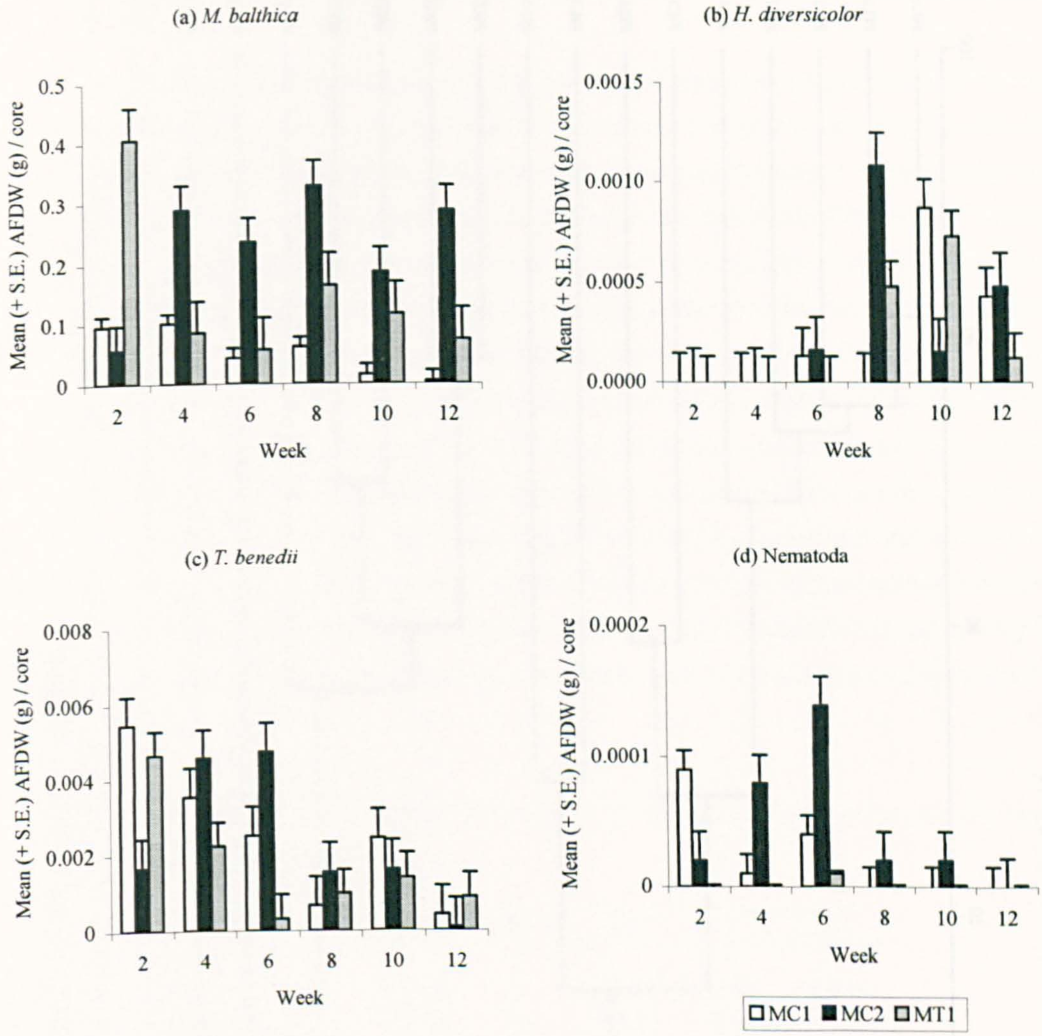


Figure 4.28 (a-d): Mean ash-free dry weight biomasses per core per sampling occasion of common taxa at the mid-shore transect 2 (+ S.E., n=3). Refer to Figure 4.6 for mid-shore control abbreviations.

4.3.4.1.8 Classification results of the mid-shore controls and treatment transect 2

The community structure in each treatment and control community at the mid-shore were divided into four groups, the smallest formed by the treatment and control communities at wk 12 (Figure 4.29). The second group indicated a similarity of mudflat control communities from wks 2 to 10. The next group included the treatment and defaunated control communities at wks 8 and 10, followed by a final group from the early stages of the experiment including the treatment and defaunated control communities.

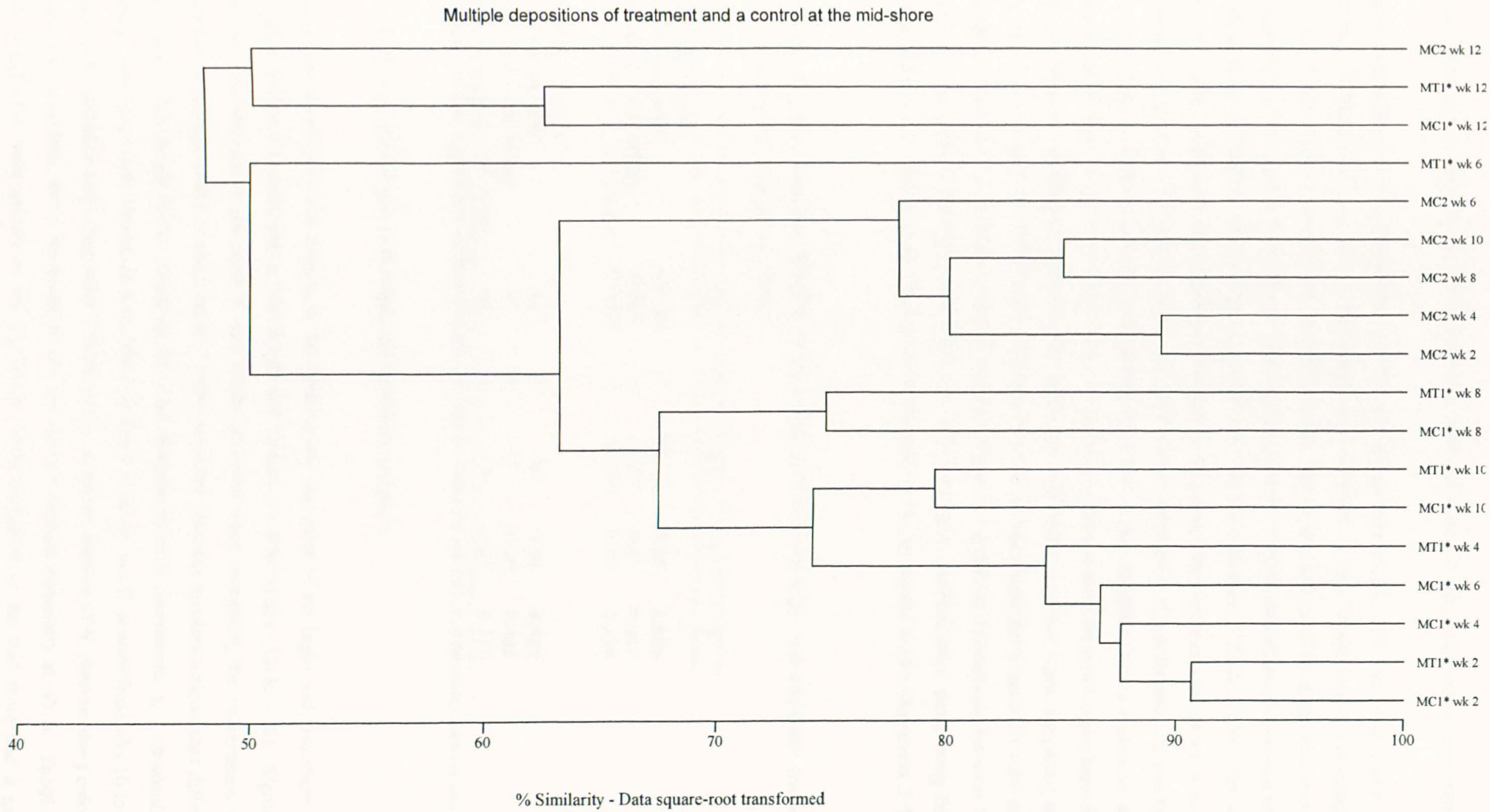


Figure 4.29: Assemblage composition similarity dendrogram of treatment type and sampling occasion at the mid-shore, transect 2.

4.3.4.1.9 Tidal height comparisons of the high- and mid-shore transect 2 - univariate community indices

The mean abundance of total individuals and the species richness at the high- and mid-shores were significantly different between time x tidal height and treatment x tidal height when comparing the controls and the treatment from wks 2 to 12 (Table 4.25). Repeated contrasts of the mean abundance of total individuals at the high- and mid-shore tidal heights showed a significant difference between time x tidal height when comparing wks 6 with 8 and wks 10 with 12 (Appendix 2 Table 4.25). The mean abundance of total individuals in the defaunated control was greater than the treatment at wk 8 and the abundance was higher in the treatment at the mid-shore when compared to the defaunated control by wk 8. Also, the high-shore had a greater mean abundance overall when compared to the mid-shore and a decrease of abundance occurred from wks 10 to 12 at the mid-shore when compared to the high-shore. The species richness significantly differed at the high- and mid-shores over time when comparing wks 2 with 4, wks 4 with 6 and wks 6 with eight, also significant differences between treatment x tidal height (Appendix 2 Table 4.25). Further repeated contrasts revealed significant interactions between time, treatment and tidal height however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Table 4.25).

Table 4.25: Repeated measures ANOVA of univariate indices at the high- and mid-shore transect 2 Control 1, Control 2 and Treatment 1 2002.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time x Tidal height	**429748**	**2**	**201422**	**8.55**	**0.009**
Treatment x Tidal height	**42303**	**2**	**21151**	**8.42**	**0.011**
Time x Treatment x Tidal height	185879	2	86695	1.70	0.239
(b) Number of species					
Time x Tidal height	**96**	**2**	**40**	**9.46**	**0.004**
Treatment x Tidal height	**73**	**2**	**37**	**24.32**	**0.000**
Time x Treatment x Tidal height	88	2	39	2.67	0.119

Bold values indicate significant differences, $p<0.05$. Refer to Figure 4.6 and Table 4.20 for control abbreviations.

4.3.4.1.10 Species abundances of the high- and mid-shore transect 2

The mean abundances of some species in the controls and treatment of the high- and mid-shore areas significantly differed between time x tidal height and treatment x tidal height (Table 4.26). Significant interactions between time x treatment x tidal height occurred when comparing the colonization of *H. diversicolor* at the high- and mid-shore areas. Further repeated contrasts revealed a significant difference between time x tidal height when comparing the mean abundances of *H. diversicolor* j, *S. shrubsolii* and Nematoda from wks 4 to 6, Nematoda from wks 6 to 8 and *H. ulvae* and *T. benedii* from wks 10 to 12 at the high- and mid-shore areas (Appendix 2 Table 4.26). A higher number of *H. diversicolor* j colonized the high-shore treatment when compared to the mid-shore treatment especially at wk 6. *Tubificoides benedii* abundances were greater at the high-shore when compared to the mid-shore and a general increase of abundance occurred from wks 2 to 12 at the high-shore but a decline in colonization was experienced from wks 10 to 12 at the mid-shore. Other, repeated contrasts revealed a significant difference between treatment x tidal height when comparing the mean abundances of *M. balthica*, *H. ulvae*, *H. diversicolor*, *H. diversicolor* j, *P. elegans* and *T. benedii* in the defaunated control and treatment; also comparisons of *H. ulvae* and *P. elegans* abundances in the mudflat control with the treatment at the high- and mid-shore areas.

Hediste diversicolor mean abundances was significantly different between time x treatment x tidal height when comparing wks 4 with 6, the defaunated control with the treatment and a greater number of individuals colonized the high-shore treatment and defaunated control when compared to the mid-shore. Nematoda mean abundances significantly differed from wks 6 to 8 when comparing the controls with the treatment between tidal heights, the highest mean abundance occurred in the mudflat control during all sampling occasions except wk 6 at the mid-shore when the treatment had the greatest mean abundance. Lastly, *H. diversicolor* mean abundance significantly differed from wks 10 to 12 when comparing the defaunated control and the treatment at the high- and mid-shore areas. The mean abundance in the treatment was equal to or greater than the defaunated control from wks 10 to 12 at the high-shore when compared to the mid-shore where the mean abundance was highest in the defaunated control. Further repeated contrasts revealed significant interactions between time, treatment and tidal height however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Table 4.26).

Table 4.26: Repeated measures ANOVA of abundance data for common taxa at the high- and mid-shore transect 2 Control 1, Control 2 and Treatment 1 2002.

Source	SS	DF	MS	F	P
(a) *A. tenuis*					
Time x Tidal height	7	2	4	0.63	0.555
Treatment x Tidal height	11	1	11	4.37	0.101
Time x Treatment Tidal height	20	2	12	0.97	0.409
(b) *M. balthica*					
Time x Tidal height	419	5	84	1.40	0.265
Treatment x Tidal height	**3088**	**1**	**2990**	**25.19**	**0.007**
Time x Treatment Tidal height	1159	2	533	1.95	0.199
(c) *H. ulvae*					
Time x Tidal height	19	2	9	2.24	0.163
Treatment x Tidal height	**8**	**2**	**4**	**18.43**	**0.001**
Time x Treatment Tidal height	26	3	10	1.33	0.313
(d) *H. diversicolor*					
Time x Tidal height	**47**	**2**	**30**	**6.59**	**0.032**
Treatment x Tidal height	**17**	**2**	**9**	**7.46**	**0.015**
Time x Treatment Tidal height	**47**	**3**	**15**	**4.15**	**0.028**
(e) *H. diversicolor* j					
Time x Tidal height	**472**	**1**	**335**	**5.79**	**0.049**
Treatment x Tidal height	**361**	**2**	**181**	**27.18**	**0.000**
Time x Treatment Tidal height	316	2	128	3.14	0.081
(f) *P. elegans*					
Time x Tidal height	6147	1	5537	1.61	0.272
Treatment x Tidal height	**11465**	**1**	**11161**	**59.35**	**0.001**
Time x Treatment Tidal height	9820	1	8823	1.47	0.293
(g) *S. shrubsolii*					
Time x Tidal height	**145**	**2**	**74**	**5.81**	**0.029**
Treatment x Tidal height	9	1	9	1.03	0.368
Time x Treatment Tidal height	53	3	20	0.86	0.481
(h) *T. benedii*					
Time x Tidal height	**219728**	**2**	**95173**	**9.20**	**0.005**
Treatment x Tidal height	**16085**	**2**	**8042**	**9.99**	**0.007**
Time x Treatment Tidal height	52613	2	29432	1.08	0.382
(i) Nematoda					
Time x Tidal height	**14520**	**2**	**8266**	**5.56**	**0.038**
Treatment x Tidal height	**9939**	**1**	**9466**	**7.40**	**0.050**
Time x Treatment Tidal height	12232	2	7782	2.83	0.137

Bold values indicate significant differences, $p<0.05$. Refer to Figure 4.6 and Table 4.20 for control abbreviations.

4.3.4.1.11 Total individuals mean biomass for each tidal height

The defaunated control had the highest total biomass of the upper-shore total individuals from wks 8 to 17; the treatment had the highest total biomass initially and was higher than the mudflat control at wks 2, 10 and 15 (Figure 4.30 a). Overall, the defaunated control had the greatest total biomass (3.3 g) at the upper-shore followed by the mudflat control (0.9 g) and the treatment (0.8 g). Initially, the defaunated control had the greatest total biomass at the high-shore and the mudflat control was highest from wks 4 to 14. The treatment had a higher total biomass at the high-shore than the defaunated control from wks 10 to 14 (Figure 4.30 b). Overall, the mudflat control had the highest total biomass at the high-shore (11.6 g) followed by the defaunated control (3.1 g) and the treatment (2.4 g). Initially, the mid-shore treatment was highest in total biomass of total individuals. Also, the treatment was higher in biomass than the defaunated control at wks 8 and 10 however, the mudflat control had the greatest biomass during wks 4 to 12 (Figure 4.30 c). In general, the mudflat control had the greatest biomass of total individuals (4.8 g) when compared to the treatment (2.5 g) and the defaunated control (1.5 g) after 6 sampling occasions over 12 weeks.

Initially, the total mean AFDW biomass at the upper-shore transect 1 differed to the trend of mean abundance of total individuals and the mudflat control had a higher AFDW than the defaunated control or the treatment. Additionally, at wks 8 and 10 the treatment had a greater AFDW than the mudflat control when compared to the total individuals, by wk 17 the defaunated control had the highest biomass unlike the total individuals in the mudflat control and had the highest mean abundance (Figure 4.31 a). The total mean AFDW biomass at the high-shore transect 2 followed a similar trend to the mean abundance of total individuals during wks 8 and 14 however, at wk 2 the defaunated control had the highest AFDW and the treatment had the least, the treatment biomass was lower than both of the controls during wks 4 to 6 when compared to the total individuals (Figure 4.31 b). The total mean AFDW biomass at the mid-shore transect 2 differed to the trend of mean abundance of total individuals initially and the treatment had a greater biomass than the controls similarly, at wks 6 and 10 the treatment had a higher AFDW than the defaunated control, by wk 12 the mudflat control AFDW was highest when compared to the total individuals (Figure 4.31 c). The high-shore had the highest total mean AFDW biomass of 5.3 (g) after 7 sampling occasions, followed by the mid-shore which had 6 sampling occasions and reached a total AFDW of 3.3 (g) and lastly the upper-shore reached a total AFDW of 0.5 (g) after 7 sampling occasions.

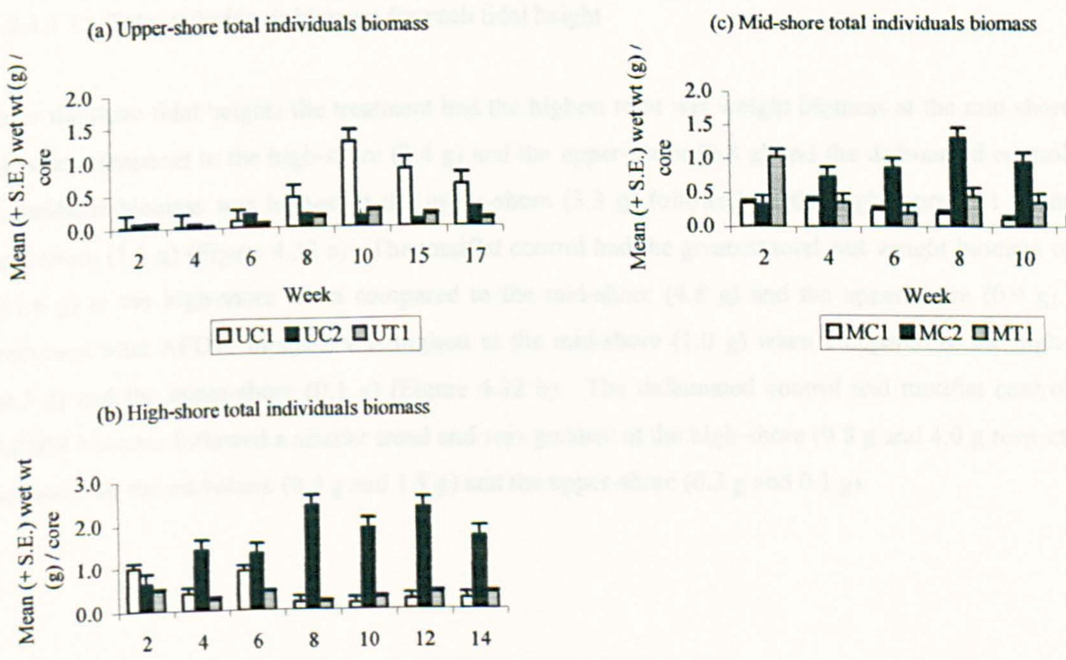


Figure 4.30 (a-c): Total individuals mean wet weight biomass per core per sampling occasion at the upper-, high- and mid-shore tidal heights (+ S.E., n=3). Refer to Figures 4.4 & 4.6 and Table 4.20 for control abbreviations.

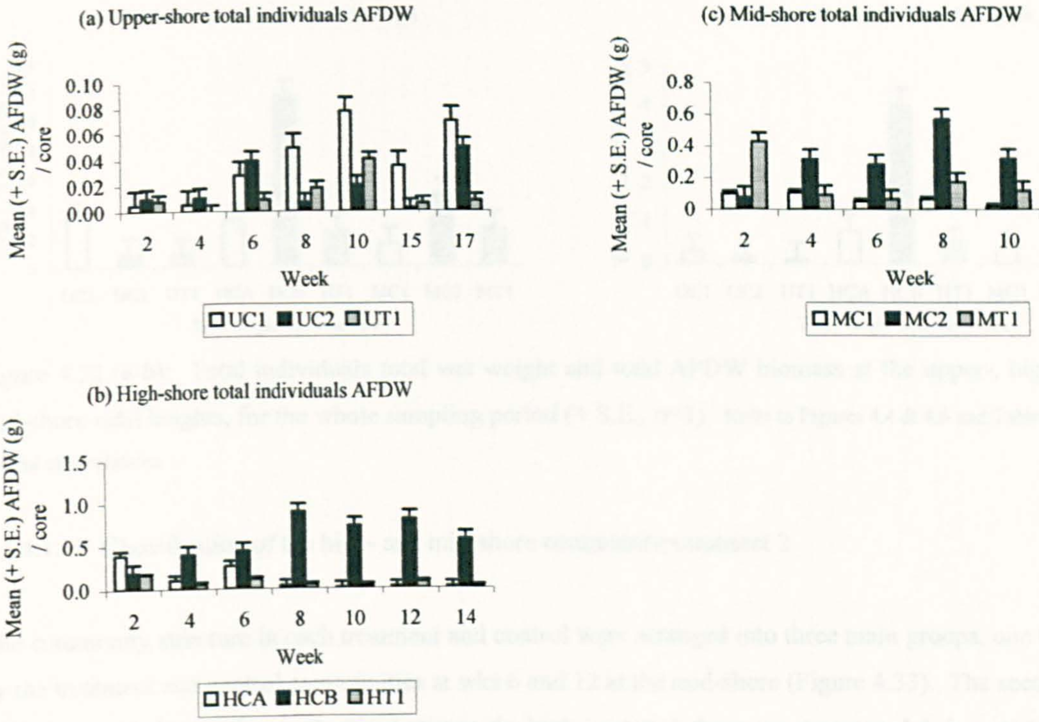


Figure 4.31 (a-c): Total individuals mean ash-free dry weight biomass per core per sampling occasion at the upper-, high- and mid-shore tidal heights (+ S.E., n=3). Refer to Figures 4.4 & 4.6 and Table 4.20 for control abbreviations.

4.3.4.1.12 Total individuals biomass for each tidal height

Over the three tidal heights the treatment had the highest total wet weight biomass at the mid-shore (2.5 g) when compared to the high-shore (2.4 g) and the upper-shore (0.8 g) and the defaunated control total individuals biomass was highest at the upper-shore (3.3 g) followed by the high-shore (3.1 g) and the mid-shore (1.5 g) (Figure 4.32 a). The mudflat control had the greatest total wet weight biomass overall (11.6 g) at the high-shore when compared to the mid-shore (4.8 g) and the upper-shore (0.9 g). The treatment total AFDW biomass was highest at the mid-shore (1.0 g) when compared to the high-shore (0.5 g) and the upper-shore (0.1 g) (Figure 4.32 b). The defaunated control and mudflat control total AFDW biomass followed a similar trend and was greatest at the high-shore (0.8 g and 4.0 g respectively) followed by the mid-shore (0.4 g and 1.9 g) and the upper-shore (0.3 g and 0.1 g).

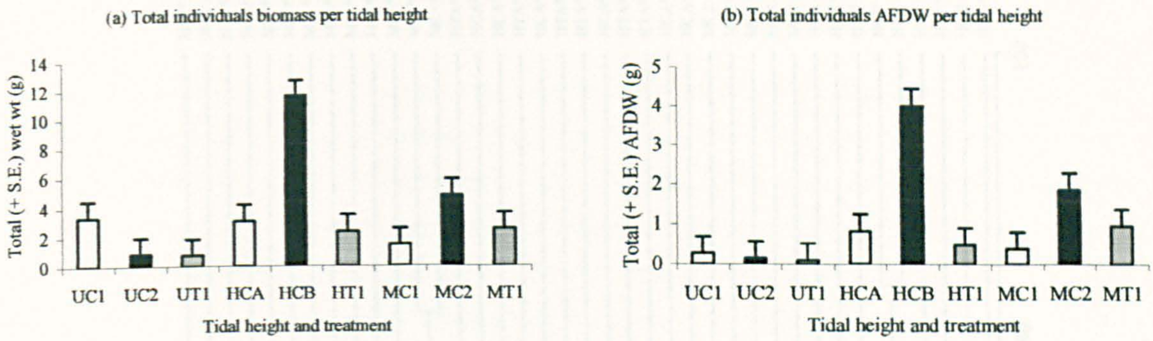


Figure 4.32 (a-b): Total individuals total wet weight and total AFDW biomass at the upper-, high- and mid-shore tidal heights, for the whole sampling period (+ S.E., n=3). Refer to Figures 4.4 & 4.6 and Table 4.20 for control abbreviations.

4.3.4.1.13 Classification of the high- and mid-shore communities transect 2

The community structure in each treatment and control were arranged into three main groups, one formed by the treatment and control communities at wks 6 and 12 at the mid-shore (Figure 4.33). The second and largest group indicates the similarities between the high- and mid-shores treatment and defaunated control communities. The third group indicates the similarities between the mudflat control communities predominantly of the high- and mid-shores.

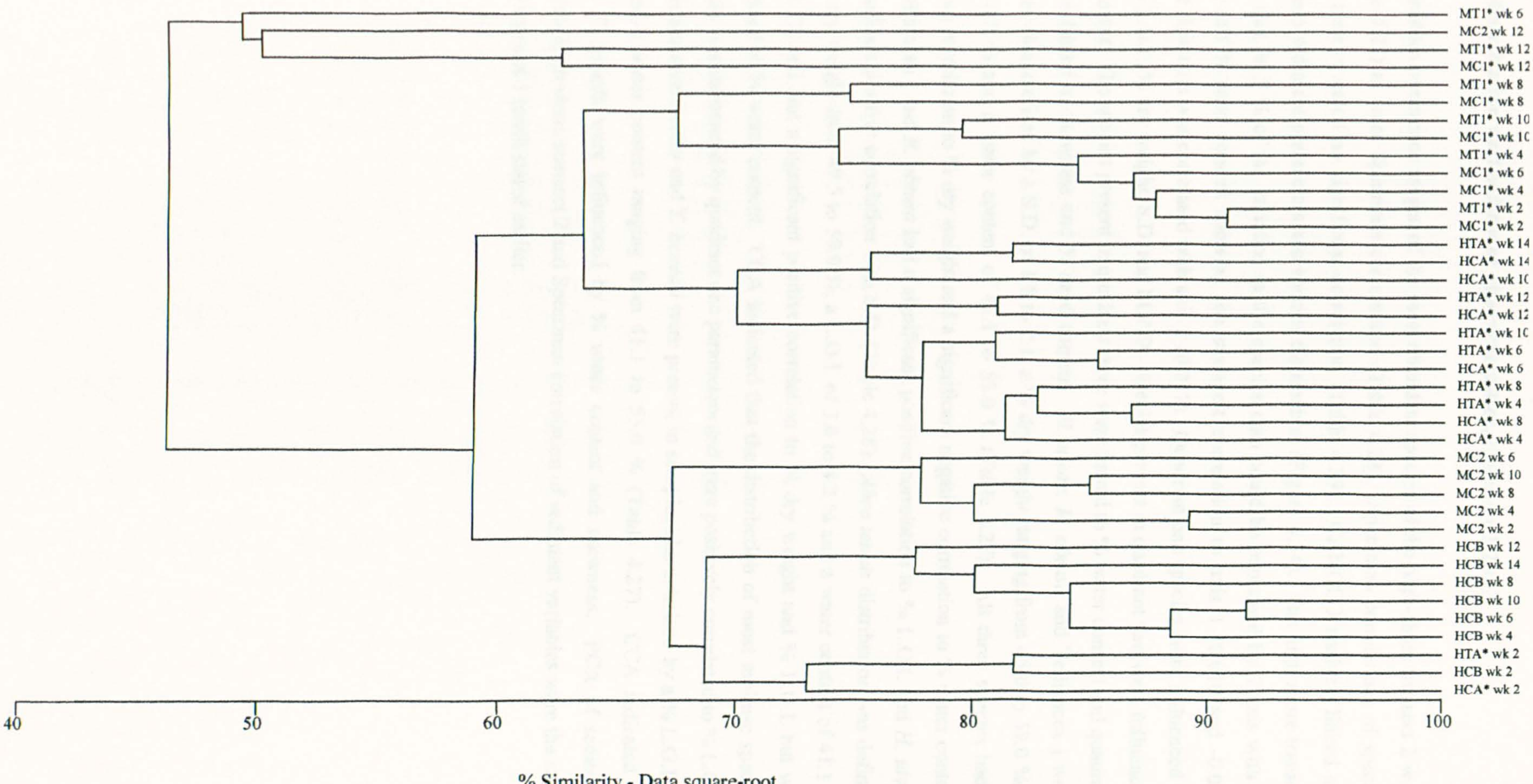


Figure 4.33: Assemblage composition similarity dendrogram of treatment type and sampling occasion at the high- and mid-shores, transect 2.

4.3.5 Species distribution and sediment characteristics, transect 2 2002

The sediment variables preference ranges of the most abundant species of the high-shore transect 2 were calculated (Table 4.27) as were Spearman correlations (Table 4.28). Spearman correlations of species abundance with time revealed no significant correlation (Table 4.29). CANOCO analysis linked any correlation between sediment parameters and species distribution (Figure 4.34). The high-shore transect 2 data indicated that 36.5 % of the variation in the species data could be explained by 2 axis with % silt/clay content and % sand content showing the strongest correlation to axis 1 (0.010 and -0.010 respectively) and skewness was correlated with axis 2 (0.017). Quadrant one species were influenced by % dry weight, % L.O.I., % dry weight, S.D. and M.P.D. Species present in quadrant two were influenced by % silt/clay content. The species present in quadrant three were linked to % water content and quadrant four species were linked to skewness and % sand content. *H. ulvae, R. obtusa* and Tellinacea j were present in samples characterised by a S.D. of 1.8 to 2.1, a % dry weight ranging from 45.0 to 59.0 %, a L.O.I. of 3.2 to 4.2 % and a water content of 41.1 to 55.0 % (Table 4.27). All three species had a significant positive correlation to % dry weight and a significant negative correlation to % water content (Table 4.28). Tellinacea j and *R. obtusa* had a significant positive correlation to % L.O.I. and *H. ulvae* had a highly significant positive correlation with S.D. (Table 4.28). *Abra tenuis* distribution was defined by a range of % dry weight from 49.5 to 59.0 %, a L.O.I. of 3.6 to 4.2 % and a water content of 41.1 to 50.5 % (Table 4.27) and had a significant positive correlation to % dry weight and % L.O.I. but was negatively correlated to % water content. CCA indicated that the distribution of most mollusc species present in the study was influenced by quadrant one parameters and were positively correlated to % L.O.I. (Table 4.28). *Hediste diversicolor* and *T. benedii* were present in samples characterised by a % L.O.I. of 3.2 to 4.2 % and a water content ranging from 41.1 to 55.0 % (Table 4.27). CCA indicated *H. diversicolor* and *T. benedii* were influenced by % water content and skewness. PCA of sediment characteristics of the high-shore transect 2 and Spearman correlation of sediment variables were the same as the high-shore transect 1 result stated earlier.

Table 4.27: Arrangement of high-shore transect 2 species according to sediment preferences.

Species	Ranges Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand	% Silt/clay	% Dry wt	% L.O.I.	% Water
A. tenuis	6.17-6.50	1.81-2.05	0.01-0.13	8.85-12.46	87.54-91.16	49.50-58.94	3.57-4.19	41.06-50.50
M. balthica	6.08-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	44.96-58.94	3.15-4.19	41.06-55.04
Tellinacea j	6.17-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	44.96-58.94	3.57-4.19	41.06-55.04
H. ulvae	6.24-6.54	1.81-2.05	-0.01-0.14	8.85-12.46	87.54-91.16	44.96-58.94	3.15-4.19	41.06-55.04
R. obtusa	6.17-6.50	1.81-2.05	-0.01-0.13	8.83-12.46	87.54-91.17	45.54-58.94	3.15-4.19	41.06-54.46
H. diversicolor	6.08-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	44.96-58.94	3.15-4.19	41.06-55.04
H. diversicolor j	6.08-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	44.96-58.94	3.15-4.19	41.06-55.04
P. elegans	6.17-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	44.96-58.94	3.15-4.19	41.06-55.04
S. shrubsolii	6.08-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	44.96-58.94	3.15-4.19	41.06-55.04
T. benedii	6.08-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	44.96-58.94	3.15-4.19	41.06-55.04
Nematoda	6.08-6.54	1.81-2.05	-0.01-0.14	8.83-12.46	87.54-91.17	44.96-58.94	3.15-4.19	41.06-55.04

Table 4.28: Significant correlations between high-shore transect 2 mean abundances of individual species and sediment characteristics, using Spearman correlation coefficient.

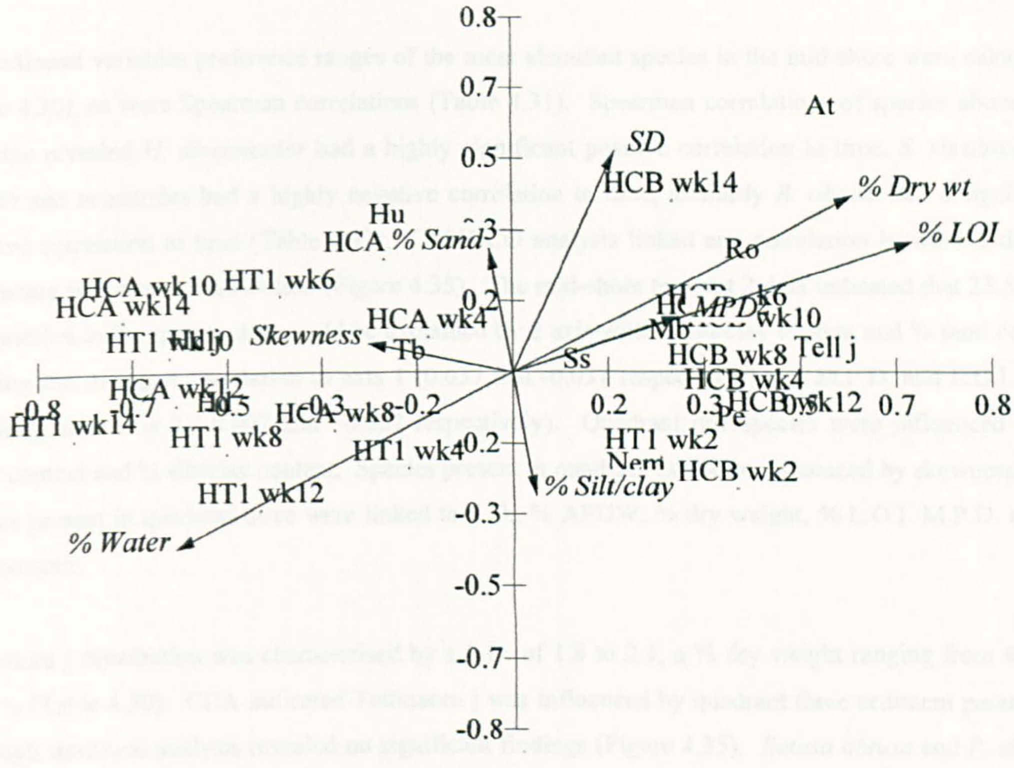
Species	Sediment characteristics Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand	% Silt/clay	% Dry wt	% L.O.I.	% Water
A. tenuis	ns	ns	ns	ns	ns	+	+	-
M. balthica	ns	ns	ns	ns	ns	ns	+	ns
Tellinacea j	ns	ns	ns	ns	ns	+	+	-
H. ulvae	ns	++	ns	ns	ns	+	ns	-
R. obtusa	ns	ns	ns	ns	ns	+	++	-
H. diversicolor	ns	ns	ns	ns	ns	ns	ns	ns
H. diversicolor j	ns	ns	ns	ns	ns	ns	ns	ns
P. elegans	ns	ns	ns	ns	ns	ns	ns	ns
S. shrubsolii	ns	ns	ns	ns	ns	ns	ns	ns
T. benedii	ns	ns	ns	ns	ns	ns	ns	ns
Nematoda	ns	ns	ns	ns	ns	ns	ns	ns

Table 4.29: Significant correlations between high-shore transect 2 mean abundance of individual species and time, using Spearman correlation coefficient.

Species	Species, treatment and week											
	A. tenuis	*M. balthica*	*Tellinacea* j	*H. ulvae*	*R. obtusa*	*H. diversicolor*	*H. diversicolor* j	*P. elegans*	*S. shrubsolii*	*T. benedii*	Nematoda	Week
A. tenuis		++	++	ns	++	--	ns	++	++	ns	+	ns
M. balthica	++		++	ns	++	--	-	++	++	ns	++	ns
Tellinacea j	++	++		ns	++	--	-	++	++	ns	++	ns
H. ulvae	ns	ns	ns		ns	ns	ns	ns	ns	ns	ns	ns
R. obtusa	++	++	++	ns		-	-	++	++	ns	+	ns
H. diversicolor	--	--	--	ns	-		ns	--	--	ns	--	ns
H. diversicolor j	ns	-	-	ns	-	ns		--	ns	ns	ns	ns
P. elegans	++	++	++	ns	++	--	--		++	ns	++	ns
S. shrubsolii	++	++	++	ns	++	--	ns	++		ns	++	ns
T. benedii	ns	ns	ns	ns	ns	ns	ns	ns	ns		ns	ns
Nematoda	+	++	++	ns	+	--	ns	++	++	ns		ns

Key

p - values		Significance
p> 0.05	ns	not significant
0.01<p<0.05	- or +	Significant negative or positive correlation
0.001<p<0.01	- - or + +	very significant negative or positive correlation



Vector scaling: 3.79

Figure 4.34: CCA of high-shore, transect 2 species distribution in relation to sediment characteristics on square-root transformed data.

Species key:

Abra tenuis (At)	*Macoma balthica* (Mb)	Tellinacea j (Tell j)
Hydrobia ulvae (Hu)	*Retusa obtusa* (Ro)	*Hediste diversicolor* (Hd)
Hediste diversicolor j (Hdj)	*Pygospio elegans* (Pe)	*Streblospio shrubsolii* (Ss)
Tubificoides benedii (Tb)	Nematoda	

4.3.5.1 Mid-shore controls and treatment, transect 2

The sediment variables preference ranges of the most abundant species in the mid-shore were calculated (Table 4.30), as were Spearman correlations (Table 4.31). Spearman correlations of species abundance and time revealed *H. diversicolor* had a highly significant positive correlation to time, *S. shrubsolii*, *T. benedii* and nematodes had a highly negative correlation to time, similarly *R. obtusa* had a significant negative correlation to time (Table 4.32). CANOCO analysis linked any correlation between sediment parameters and species distribution (Figure 4.35). The mid-shore transect 2 data indicated that 23.5 % of the variation in the species data could be explained by 2 axis with % silt/clay content and % sand content showing the strongest correlation to axis 1 (0.037 and -0.037 respectively) and M.P.D. and L.O.I. were correlated with axis 2 (-0.007 and –0.027 respectively). Quadrant one species were influenced by % water content and % silt/clay content. Species present in quadrant two were influenced by skewness. The species present in quadrant three were linked to S.D., % AFDW, % dry weight, % L.O.I. M.P.D. and % sand content.

Tellinacea j distribution was characterised by a S.D. of 1.8 to 2.1, a % dry weight ranging from 46.1 to 57.1 % (Table 4.30). CCA indicated Tellinacea j was influenced by quadrant three sediment parameters although statistical analysis revealed no significant findings (Figure 4.35). *Retusa obtusa* and *P. elegans* distributions were defined by a % L.O.I. of 3.1 to 4.1 % and a water content of 41.8 to 55.6 % (Table 4.30). Spearman correlation revealed *R. obtusa* had a significant positive correlation to % water content (Table 4.31). CCA indicated the distribution of *R. obtusa* and *P. elegans* were influenced by quadrant three sediment parameters. *Macoma balthica, H. ulvae, S. shrubsolii* and *T. benedii* were characterised by samples with a S.D. of 1.8 to 2.1, a % dry weight of 44.4 to 58.2 %, a % L.O.I. of 3.1 to 4.1 % and a water content ranging from 41.8 to 55.6 % (Table 4.30). A Spearman correlation revealed *M. balthica* had a highly significant negative correlation to S.D., % dry weight and % L.O.I. and a significant negative correlation to % water content (Table 4.31). CCA indicated all species in quadrant one had the same sediment characteristic influences of % water content and % silt/clay content. *Hediste diversicolor* distribution was defined by a % sand content ranging from 9.7 to 12.7 %, a S.D. of 1.8 to 2.1 and a % water content of 41.8 to 55.1. CCA indicated *H. diversicolor* distribution was correlated to axis 1.

Table 4.30: Arrangement of mid-shore transect 2 species according to sediment preferences.

Species	Ranges							
	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content
M. balthica	6.15-6.58	1.81-2.11	0.00-0.13	8.68-12.74	87.26-91.32	44.37-58.22	3.13-4.11	41.78-55.63
Tellinacea j	6.19-6.58	1.83-2.11	0.01-0.13	9.40-12.74	87.26-90.60	46.08-57.12	3.65-4.05	42.88-53.92
H. ulvae	6.15-6.58	1.81-2.11	0.00-0.13	8.68-12.74	87.26-91.32	44.37-58.22	3.13-4.11	41.78-55.63
R. obtusa	6.19-6.58	1.83-2.11	0.00-0.13	8.68-12.74	87.26-91.32	44.37-58.22	3.28-4.11	41.78-55.63
H. diversicolor	6.15-6.58	1.81-2.11	0.00-0.13	9.77-12.74	87.26-90.23	44.86-58.22	3.13-4.11	41.78-55.14
H. diversicolor j	6.15-6.51	1.81-1.99	0.01-0.13	9.08-11.47	88.53-90.60	44.86-58.22	3.13-4.11	41.78-55.14
N. hombergii	6.15-6.58	1.83-1.99	0.00-0.13	8.68-12.74	87.26-91.32	44.37-58.22	3.13-4.11	41.78-55.63
P. elegans	6.15-6.58	1.83-2.11	0.00-0.13	8.68-12.74	87.26-91.32	44.37-58.22	3.13-4.11	41.78-55.63
S. shrubsolii	6.15-6.58	1.83-2.11	0.00-0.13	8.68-12.74	87.26-91.32	44.37-58.22	3.13-4.11	41.78-55.63
T. benedii	6.15-6.58	1.81-2.11	0.00-0.13	8.68-12.74	87.26-91.32	44.37-58.22	3.13-4.11	41.78-55.63
Nematoda	6.15-6.58	1.81-2.11	0.00-0.13	8.68-12.74	87.26-91.32	44.37-58.22	3.13-4.11	41.78-55.63

Table 4.31: Significant correlations between mid-shore mean abundance of individual species and sediment characteristics, using Spearman correlation coefficient.

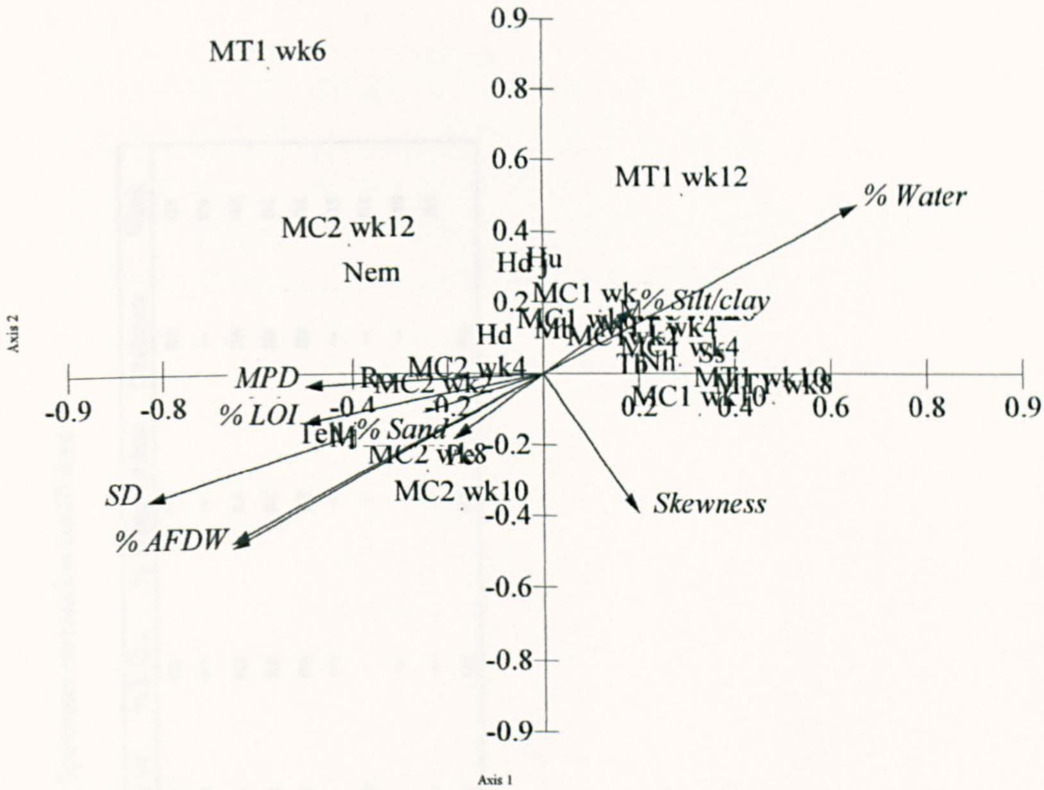
Species	Sediment characteristics							
	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content
M. balthica	ns	–	ns	ns	ns	–	–	-
Tellinacea j	ns	ns	ns	ns	ns	ns	ns	ns
H. ulvae	ns	ns	–	ns	ns	ns	ns	ns
R. obtusa	+	ns	ns	ns	ns	ns	ns	+
H. diversicolor	ns	ns	ns	ns	ns	ns	ns	ns
H. diversicolor j	ns	ns	ns	ns	ns	ns	ns	ns
N. hombergii	ns	ns	ns	ns	ns	ns	ns	ns
P. elegans	ns	ns	ns	ns	ns	ns	ns	ns
S. shrubsolii	ns	ns	ns	ns	ns	ns	ns	ns
T. benedii	ns	ns	ns	ns	ns	ns	ns	ns
Nematoda	ns	ns	ns	ns	ns	ns	ns	ns

Table 4.32: Significant correlations between mid-shore transect 2 mean abundance of individual species and time, using Spearman correlation coefficient.

Species	Species, treatment and week											
	M. balthica	*Tellinacea* j	*H. ulvae*	*R. obtusa*	*H. diversicolor*	*H. diversicolor* j	*N. hombergii*	*P. elegans*	*S. shrubsolii*	*T. benedii*	Nematoda	Week
M. balthica		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Tellinacea j	ns		ns	++	ns	ns	+	++	ns	ns	+	ns
H. ulvae	ns	ns		ns	ns	ns	ns	ns	ns	ns	ns	ns
R. obtusa	ns	++	ns		ns	ns	ns	++	+	+	++	-
H. diversicolor	ns	ns	ns	ns		ns	ns	ns	-	ns	ns	++
H. diversicolor j	ns	ns	ns	ns	ns		ns	ns	ns	ns	ns	ns
N. hombergii	ns	+	ns	ns	ns	ns		ns	ns	ns	ns	ns
P. elegans	ns	++	ns	++	ns	ns	ns		++	++	+	ns
S. shrubsolii	ns	ns	ns	+	-	ns	ns	++		++	ns	--
T. benedii	ns	ns	ns	+	ns	ns	ns	++	++		ns	--
Nematoda	ns	+	ns	++	ns	ns	ns	+	ns	ns		--

Key

p - values		Significance
p> 0.05	ns	not significant
0.01<p<0.05	- or +	Significant negative or positive correlation
0.001<p<0.01	- - or + +	very significant negative or positive correlation



Vector scaling: 4.80

Figure 4.35: CCA of mid-shore, transect 2 species distribution in relation to sediment characteristics on square-root transformed data.

Species key:

Macoma balthica (Mb)	*Hediste diversicolor* (Hd)	*Streblospio shrubsolii* (Ss)
Tellinacea j (Tell j)	*Hediste diversicolor* j (Hdj)	*Tubificoides benedii* (Tb)
Hydrobia ulvae (Hu)	*Nephtys hombergii* (Nh)	Nematoda
Retusa obtusa (Ro)	*Pygospio elegans* (Pe)	

Treatment type had a highly significant negative correlation to S.D., % dry weight, % L.O.I. and % water content, the factor time was not significantly correlated to any sediment parameter (Table 4.33). PCA divided the mid-shore treatment and controls into three clusters (Figure 4.36). Group one was characterised by an increased water content when compared to the remaining groups and contained all of the mid-shore treatments and had a water content ranging from 49.8 to 55.6% (Table 4.34). Groups two and three were influenced by a water content of 44.8 to 46.2 % and 41.8 to 43.0 % respectively. Group two had a lower % dry weight of 53.8 to 55.1 % when compared to group three (57.0 to 58.2 %) and group two had lower sand content (9.1 to 10.7 %) than group three (9.9 to 12.7 %).

Table 4.33: Significant correlations between mid-shore transect 2 sediment characteristics, using Spearman correlation coefficient.

Sediment variables	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content	Treatment	Week
Inc. M.P.D. Ø		+	--	--	++	ns	ns	++	ns	ns
Inc. S.D. Ø	+		ns	ns	ns	++	++	+	--	ns
Inc. Skewness	--	ns		++	--	ns	ns	ns	ns	ns
% Sand content	--	ns	++		--	ns	ns	ns	ns	ns
% Silt/clay content	++	ns	--	--		ns	ns	ns	ns	ns
% Dry wt	ns	++	ns	ns	ns		++	+	--	ns
% L.O.I.	ns	++	ns	ns	ns	++		+	--	ns
% Water content	++	+	ns	ns	ns	+	+		--	ns
Treatment	ns	--	ns	ns	ns	--	--	--		ns
Week	ns	ns	ns	ns	ns	ns	ns	ns	ns	

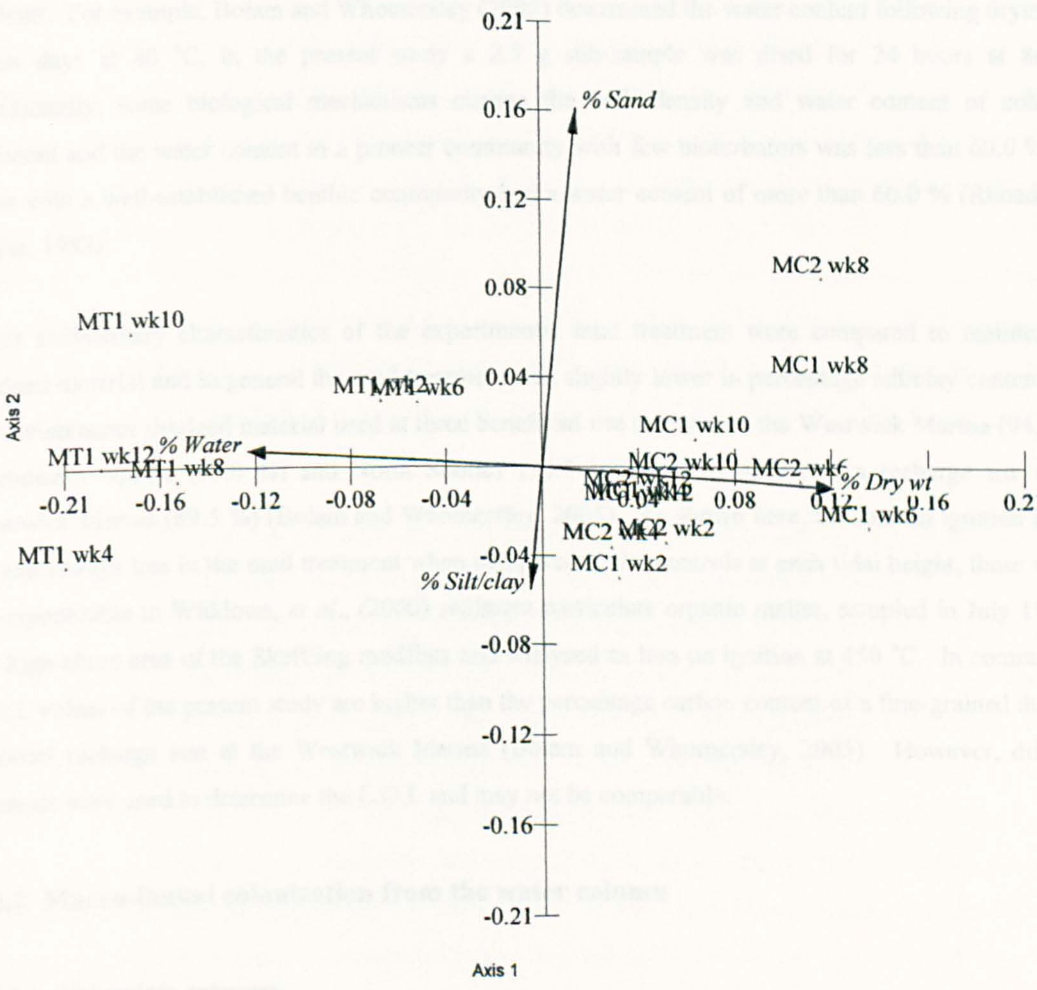
Key

p - values		Significance
p> 0.05	ns	not significant
0.01<p<0.05	- or +	Significant negative or positive correlation
0.001<p<0.01	- - or + +	very significant negative or positive correlation

Table 4.34: Analysis of mid-shore, transect 2 groups sorted by PCA according to sediment characteristics.

Group	Site	Features
1	MT1 wk 2 MT1 wk 4 MT1 wk 6 MT1 wk 8 MT1 wk 10	Water content between 49.77 & 55.63% Silt/clay % between 88.67 & 91.32%
2	MC1 wk 2 MC1 wk 4 MC1 wk 10 MC1 wk 12 MC2 wk 2 MC2 wk 4 MC2 wk 10 MC2 wk 12	Water content between 44.82 & 46.17% Dry wt % between 55.83 & 55.10% LOI % between 3.65 & 4.05%. Sand % between 9.08 & 10.65%.
3	MC1 wk 6 MC1 wk 8 MC2 wk 6 MC2 wk 8	Water content between 41.78 & 43.04%. LOI % between 3.72 & 4.11%. Sand % between 9.86 & 12.74%. Dry wt % between 56.96 & 58.22%.

Refer to Figure 4.6 for control abbreviations.



Vector scaling: 0.18

Figure 4.36: PCA of the sediment characteristics of the mid-shore transect 2 treatment and controls on square-root transformed data. Refer to Figure 4.6 for control abbreviations.

4.4 Discussion

4.4.1 Sediment variables

The mud treatment of the present study was lower in water content when compared to the fine-grained maintenance dredged material slurry (of 60.0 % water content) generated during a beneficial use scheme at a North Shotley mudflat, along the Orwell Estuary, UK and of the recharge site at the same location (of 55.0 % water content) (Bolam and Whomersley, 2005). The beneficial use of dredged material is a relatively new method used in coastal management and the exact water content of the slurry generated in a beneficial use scheme was unavailable when the current study was implemented. Some differences may occur in the methods used to determine the water content of sediments making inter-study comparisons difficult. For example, Bolam and Whomersley (2005) determined the water content following drying for seven days at 80 °C, in the present study a 2.5 g sub-sample was dried for 24 hours at 86 °C. Additionally, some biological mechanisms change the bulk density and water content of cohesive sediment and the water content in a pioneer community with few bioturbators was less than 60.0 %, but areas with a well-established benthic community had a water content of more than 60.0 % (Rhoads and Boyer, 1982).

Other sedimentary characteristics of the experimental mud treatment were compared to maintenance dredged material and in general the mud treatment was slightly lower in percentage silt/clay content than the maintenance dredged material used at three beneficial use schemes at the Westwick Marina (94.5 %), Titchmarsh Marina (95.0 %) and North Shotley (93.7 %) but was similar to a recharge site at the Westwick Marina (89.5 %) (Bolam and Whomersley, 2005). As shown here, the loss on ignition at 475 °C was always less in the mud treatment when compared to the controls at each tidal height, these values are comparable to Widdows, *et al.*, (2000) sediment particulate organic matter, sampled in July 1996 at the high-shore area of the Skeffling mudflats and analysed as loss on ignition at 450 °C. In contrast, the L.O.I. values of the present study are higher than the percentage carbon content of a fine-grained dredged material recharge site at the Westwick Marina (Bolam and Whomersley, 2005). However, different methods were used to determine the L.O.I. and may not be comparable.

4.4.2 Macro-faunal colonization from the water column

4.4.2.1 Univariate recovery

The sampling of macro-faunal communities over a 17-week period of the present study over 3 tidal heights enabled the evaluation of spatial and temporal changes in colonist communities over a spring-summer period. The deposition of a manipulated water content mud treatment placed in multiple small amounts to a total depth of 14 cm demonstrated the establishment of a rich and diverse macro-faunal assemblage over one spring-summer season. The high-shore experimental areas were colonized well and total macro-faunal densities reached 15173 and 14601. These are comparable to the total abundance of macro-fauna (12000) colonizing the experimental sediment treatments placed on a mudflat in the Crouch

Estuary and re-colonized for a period of 12 months (Bolam, *et al.*, 2004) although less colonization occurred at the mid-shore (7190) of the current study and decreased further at the upper-shore (5579). In contrast, the total abundance of individuals colonizing a Crouch Estuary recharge scheme was much greater (36136) following 18 months of macro-faunal recovery (Bolam and Whomersley, 2003).

During this study, the macro-faunal re-colonization of the upper-shore mud treatment was similar to the natural mudflat and defaunated control levels and no significant differences occurred between the factors treatment and time. Initially, the species diversity of the upper-shore mud treatment was greater than the controls but subsequently reversed and either the natural mudflat level or the defaunated control demonstrated a greater diversity. Unlike the upper-shore, statistical analysis revealed significant differences of total individuals between the factors treatment and time at the high-shore and a significant difference in macro-faunal recovery occurred over time. Additionally, significant differences occurred between the mud treatment and both the controls, for example, the macro-faunal colonization of the mud treatment and controls were good initially. This was followed by a subsequent decrease in general colonization towards the mid summer period before an increased colonization event from July onwards and community analysis revealed a similarity between the communities of the mud treatment and defaunated control of July to September. By the middle of July a peak recovery of total individuals occurred in the mud treatment. In addition, the species richness of the high-shore mud treatment significantly differed to the mudflat level and more species colonized the treatment initially. However, from early June onwards an increase in the number of mudflat species occurred. In general, the species diversity of the mud treatment did not reach the higher levels of the natural mudflat or the defaunated control.

The re-colonization of a second high-shore experimental area revealed significant differences of total individuals recovery between the treatment types. Further analysis revealed a significant difference of macro-faunal colonization of the mud treatment and defaunated control, the initial macro-faunal recovery was greatest in the mud treatment but later fluctuated between a higher or lower amount of colonization when compared to the defaunated control. However, the total densities did not reach the natural mudflat level. The community analysis revealed a similarity between the high-shore communities of the mud treatment and controls during the early experimental stages, suggesting the amount of macro-faunal recovery was comparable. Additionally, the recovery of species richness in the mud treatment was significantly less than the mudflat species richness and on most sampling occasions the mudflat species diversity was greater than the mud treatment or the defaunated control. At the mid-shore, the total macro-faunal densities colonizing the mud treatment and controls significantly differed between treatment type and the recovery of the mud treatment did not reach the natural mudflat level. However, the initial macro-faunal colonization of the mud treatment appeared similar to the controls but later fluctuated between a higher or lower amount when compared to the defaunated control.

4.4.2.2 Spatial and temporal differences in treatment colonization

The dominant taxa of this study are *T. benedii*, followed by macro-faunal nemtodes, *P. elegans* and *M. balthica*. Similarly, some of these species were the dominant taxa colonizing a recharge scheme: *T. benedii*, *S. shrubsolii*, *Corophium volutator* (Pallas), nemtodes and *H. diversicolor* (Bolam and Whomersley, 2003). Early colonizers of this study included *H. diversicolor*, *T. benedii* and nematodes and other species colonized the mud treatment and controls of the high- and mid-shore areas towards the latter part of the experiment i.e. from mid- to late-summer, such as *C. maenas* and *P. cornuta*. Other species colonized mostly the high-shore microcosms; *Scrobicularia plana* (de Costa), *Eteone longa/flava* agg (Fabricius), *M. aestuarina* and *Tharyx* "A" (Unicomarine). Also, some species colonized the mid-shore microcosms only, such as *Cerasterderma edule* (Linnaeus), *Cirratulidae* juveniles and *Nephyts hombergii* (Savigny) and taxon such as Tellinacea juveniles, *H. diversicolor*, *T. benedii* and Nematoda colonized the high-shore treatment and controls in greater abundances when compared to the mid-shore and *P. elegans* was more abundant in the mid-shore treatment and controls.

During the study, a number of significant spatial and temporal differences were highlighted between tidal heights. For example, the total macro-faunal densities were significantly different over time and more individuals colonized the high-shore (transect 1) microcosms towards the latter period of the experiment when compared to the upper-shore, following 17 weeks of recovery. Similarly, a significant difference in macro-faunal recovery occurred over time between the high- and mid-shore tidal heights and more individuals colonized the high-shore following 14 weeks of macro-faunal recovery. For example, more *H. diversicolor* and *T. benedii* individuals colonized the high-shore (transect 2) when compared to the mid-shore. Other factors such as treatment type differed between tidal heights and the total macro-faunal density of the mud treatment significantly differed to the defaunated control between tidal heights and the high-shore densities were significantly greater than the upper-shore. However, in June the macro-faunal recovery of transect 1 was low and community analysis revealed a similarity between the mud treatment and defaunated control communities of the upper- and high-shore and the upper-shore mudflat community in June, whilst the high-shore mudflat community in June was more similar to the high-shore mudflat communities of the latter period of the experiment. This was due to a richer and more diverse high-shore mudflat community consisting of increased numbers of numerically dominant species, especially *T. benedii*, Nematoda and *M. balthica*. Some differences of nematode colonization occurred between tidal heights. For example, a significantly greater density of nematodes colonized the upper-shore mud treatment and defaunated control when compared to the high-shore (transect 1) and a significant increase of nematode colonization occurred at the mid-shore in late May and was especially high in the mud treatment, whilst an overall decrease occurred at the high-shore (transect 2). Nematode colonization ability was not affected by an increase of sediment water content.

The initial recovery of a dredged material recharge scheme was rapid at the Westwick Marina, along the Crouch Estuary (Bolam and Whomersley, 2003), although the recharge amount was placed to a greater depth than the current study and ranged from 49 cm to 57 cm. Like the present study, Bolam and Whomersley (2003) reported significant differences of macro-faunal community structure at the recharge and control sites between tidal heights. They concluded the macro-faunal community recovery of a fine-grained sediment recharge scheme could take place within one year, although the primary recovery mechanism could not be unequivocally attributed to one method alone such as larval recruitment or active adult migration. Other studies suggest the larval recruitment of taxa from undisturbed areas and immigration of adults via horizontal migration from undisturbed areas, could explain the gradual re-establishment of a benthic community observed at one and two year old dredged material disposal sites (Harvey, *et al.*, 1998).

The species richness of the mud treatment was significantly different when compared to the mudflat and between tidal heights and significantly more species colonized the high-shore mudflat area than the mud treatment when compared to the upper-shore. In comparison, the species richness of the high-shore (transect 2) mud treatment and controls were significantly greater than the mid-shore. Over the tidal heights, the mud treatment had the greatest biomass of total individuals at the mid-shore (2.5 g) when compared to the treatment biomass at the high-shore (transect 2) (2.4 g) and the upper-shore (0.8 g). Only the upper-shore total individuals biomass was similar to the mudflat biomass, the high- and mid-shore biomasses remained diverged from the natural mudflat biomass. In contrast, the wet weight biomass per core, following 12 months of macro-faunal recovery at three beneficial use schemes, were less than or equal to the mud treatment biomass of this study. For example, the biomasses were 1 g, 0.8 g and 0.4 g at the Titchmarsh Marina, Westwick Marina and North Shotley sites respectively (Bolam and Whomersley, 2004). Decreases in macro-faunal abundances and/or biomasses as a consequence of the disposal of dredged material have been reported in some studies (Zimmerman, *et al.*, 2003; Cruz-Motta and Collins, 2004). Another found a high level of macro-faunal recovery but with a change of community structure (Powilleit, *et al.*, 2006) whilst others have found no detrimental effects of total abundance (Van Dolah, *et al.*, 1984; Harvey, *et al.*, 1998; Smith and Rule, 2001). Other studies have shown a decrease in the number of species, densities and biomass, following a short recovery such as the results found by Leathem, *et al.*, (1973) when dredged material was placed adjacent to a breakwater. Differences in the recovery of univariate community indices occurred between beneficial use schemes. For example, the recovery of a recharge scheme at North Shotley took place within one year and univariate indices were comparable to a reference site. However, at other recharge schemes macro-faunal recovery responded differently and the total individuals and species richness of a recharge site at the Titchmarsh Marina were significantly less than a reference site (Bolam and Whomersley, 2005).

As shown here, few *M. balthica* individuals colonized the upper-shore microcosms. However, this species was regarded a good colonizer of simulated dredged material treatment in Chapter 3 and demonstrated an adept ability to vertically and horizontally migrate into defaunated sediment to a depth of 50 cm and 27 cm. However, in the present study treatment type was a significant factor for *M. balthica* colonization. Bivalves can actively enter the water column by burrowing towards the sediment surface, a secretion from the byssus glands allows some individuals to drift on small currents and be passively transported to new areas (Sigurdsson, *et al.*, 1976) and in turn this process may facilitate active sediment selection. For example, Huxham and Richards (2003) determined larger size classes of *M. balthica* were significantly associated with a muddy sediment type and *C. edule* was associated with a sandy sediment. In some instances macro-faunal recovery is not affected by the deposition of dredged material as was demonstrated by Powilleit, *et al.*, (2006). For example, the colonization of the bivalves *M. balthica* and

Arctica islandica (Linnaeus) at an experimental dredged material disposal area in Mecklenburg Bay in the Baltic Sea were not significantly affected by the disposal. However, in the present study *M. balthica* colonization of the mud treatment and defaunated control significantly differed between tidal heights and more individuals colonized the mud treatment and defaunated control when deposited at the high-shore (transect 1). A different trend emerged when comparing the tidal heights of the high-shore (transect 2) and the mid-shore and the ability of *M. balthica* to colonize the mud treatment and defaunated control significantly differed between the tidal heights and more individuals colonized the mid-shore treatment and defaunated control. The colonization of *M. balthica* in this study was negatively correlated to the sediment water content and the densities of the mud treatment and defaunated control did not reach the natural mudflat level. Therefore like the high-shore (transect 1) results, an increase of water content to 40.0 % such as that of the manipulated mud treatment used in this experimental study could be a limiting factor of *M. balthica* colonization.

According to Gunther (1991) the distribution of *M. balthica*, post-larval colonization was related to tidal height and seasonal variation. For example, during the summer, the high-shore contained the greatest density and during winter migrations post-larval transport and dominance were directed towards the sublittoral. Beukema, *et al.*, (1999) observed a number of species in the water column above a Wadden Sea tidal flat and high densities of juvenile *M. balthica* were caught in the winter and spring periods and more post-larval stages were caught in the summer. Turner, *et al.*, (1997) investigated the effects of bedload and water-column transport on the dispersal and colonization by post-settlement macro-fauna, using pans of defaunated sediment, bedload and water column traps. They concluded that the transportation and deposition of post-settlement stages of colonizing macro-fauna might be passive processes. Indeed, Norkko, *et al.*, (2001) concluded that the post-settlement dispersal of juvenile bivalves was dispersed at a scale of meters within a single tidal cycle. The high-shore area of intertidal flats is commonly used as nursery areas by juvenile *M. balthica* (Hiddink, *et al.*, 2002). According to Hiddink, *et al.*, (2002) predation by birds of high densities of 0- and 1+ group *M. balthica* present at the high-shore was low. However, predation by 0-group *C. maenas*, that were abundant at this tidal height, was high. Therefore, the successful re-colonization of *M. balthica* at a recharge site may be dependent on the type of bird species present and the ability of epibenthic predators to re-colonize the site.

The colonization of sedimentary habitats by larval recruitment can occur through passive settlement via transportation in the sediment bedload (Grant, *et al.*, 1997) or selective settlement (Butman, *et al.*, 1988; Turner, *et al.*, 1997). For example, Mosksnes (2002) conducted a series of field mesocosm and cage experiments and concluded that the shore crab *C. maenas* actively selected a habitat preference at settlement, although subsequent secondary dispersal modification of habitat selection by juveniles dictated the distributional range. Indeed, Richards, *et al.*, (1999) demonstrated the distribution of *C. maenas* was sediment-specific, preferring a muddy substrate to a sandy. *Carcinus maenas* individuals did not colonize the high-shore (transect 2) treatment until late July and the mid-shore defaunated control during June/July, however densities were low. In contrast, more individuals colonized the microcosms of the upper- and high-shore (transect 1) and were present from July to September. Other crustacea such as the amphipod *C. volutator* was the dominant colonizer of a dredged material beneficial use scheme at the

Westwick Marina (Bolam and Whomersley, 2003). Few *C. volutator* individuals colonized the treatment microcosms of the present study and numbers were generally low in the mudflat controls.

Another adept colonizer was *T. benedii* (see Chapters 2 and 3) and its distribution was widespread in the sediment vertical profile, in the present study individuals colonized the upper-shore mud treatment, but were especially abundant in the defaunated control. In contrast, more individuals colonized the high-shore (transect 1) mud treatment when compared to the colonization of upper-shore mud treatment. This trend was reflected in the colonization of the upper- and high-shore defaunated controls and more individuals colonized the high-shore. Similarly, individuals colonized the high- and mid-shores (transect 2) and significantly differed between late June and early July. A general increase of abundance occurred at the high-shore during this period and a decrease at the mid-shore. Overall, significantly higher *T. benedii* densities colonized the high-shore mud treatment and defaunated control when compared to the mid-shore and are comparable to the mean abundances of *T. benedii* at two recharge schemes: Westwick Marina (171.7) and North Shotley (215) following 12 months of recharge placement (Bolam and Whomersley, 2005).

Of the polychaete species colonizing the microcosms of this study, a greater density of the errant Nereid *H. diversicolor* colonized the upper- and high-shore (transect 1) mud treatment when compared to the natural mudflat control and colonization began from early July onwards. At the mid-shore the overall *H. diversicolor* colonization of the mud treatment was low in comparison to the high-shore (transect 2) and a significant increase of *H. diversicolor* colonization of the mud treatment occurred from June to early July when compared to the mudflat control, whilst colonization was low at mid-shore during this period.

A disturbance event can create an opportunity for new individuals to become established and *H. diversicolor* demonstrated a good recovery after six-months, following the impact of a pipeline construction at Clonakilty Bay, West Cork, Ireland. The re-colonization was facilitated by high *H. diversicolor* densities present in the surrounding area (Lewis, *et al.*, 2003). In comparison, an increased amount of *H. diversicolor* individuals colonized a recharge scheme at the Westwick Marina following 12 months of dredged material placement, however, initial colonization was low (Bolam and Whomersley, 2003). Conversely, in the present study, a greater number of juvenile *H. diversicolor* colonized the upper-shore mud treatment initially when compared to the high-shore (transect 1) and a significant increase of *H. diversicolor* juveniles colonized the mud treatment in May at the high-shore (transect 2) when compared to the mid-shore. In a sediment manipulation experiment, Beukema, *et al.*, (1999) demonstrated that after six months of recovery between April and October of defaunated sediment at the Wadden Sea, many macro-faunal species were present in high densities, especially juveniles of *Nereis* and bivalve spat including *M. balthica*, although few large-sized adult *Nereis* and *M. balthica* did not colonize the defaunated plots. Rasmussen (1973) noted the main reproductive period for *H. diversicolor* is between March and April and is a time of non-pelagic development from May (Bartels-Hardege and Zeeck, 1990). A period of juvenile settlement from the water column was demonstrated by an increased colonization of the mud treatment microcosms at the upper- and high-shore (transect 2). In comparison, an *in situ* benthic community development in defaunated sediment was examined by Diaz-Castaneda, *et al.*, (1993). Polychaeta was the dominant re-colonizing group and larval recruitment accounted for the greatest method of re-colonization. In this study, more Spionid polychaetes *P. elegans* and *S. shrubsolii* significantly colonized the mud treatment and defaunated control when placed at the mid-shore in comparison to the high-shore (transect 2) and a greater abundance of *P. elegans* inhabited the mid-shore mudflat control.

4.4.3 Factors affecting macro-faunal recovery

4.4.3.1 Sediment water content

The colonization of *H. ulvae* significantly differed between the mud treatment and controls of the upper- and high-shores (transect 1) and the mud treatment densities remained dissimilar to those of the controls of the upper-shore. Indeed *H. ulvae* colonization at the upper- and high-shores was negatively correlated to sediment water content. However, densities at the high-shore (transect 1) and mid-shore mud treatments were similar to the natural mudflat level. *Hydrobia ulvae* demonstrated a good ability to re-colonize a recharge scheme at the Titchmarsh Marina (Bolam and Whomersley, 2005) and the mean abundance (252) was much higher than the colonization of the mud treatment in the current study. Similarly, *H. ulvae* successfully re-colonized a defaunated area of mudflat at the Wadden Sea following a six-month recovery period (from April to October) and was demonstrated by Beukema, *et al.*, (1999). In general, only the mollusc species colonizing the mud treatment microcosms of this study appeared to be negatively correlated to the sediment water content, for example, *M. balthica* (discussed earlier) and juvenile Tellinacea, although at the mid-shore *R. obtusa* colonization was positively correlated to the sediment water content. A conceptual model of multiple depositions of manipulated sediment treatment was constructed and macro-faunal community response was compared in the general discussion (Chapter 6).

4.4.3.2 Sediment silt/clay and organic contents

The distribution of macro-fauna was not significantly correlated with the silt/clay content of the mud treatment and controls when placed at the upper-, high- or mid-shore areas. In contrast, the species richness of beneficial use schemes was negatively correlated with percentage silt/clay content and the total individuals were negatively correlated with redox potential (Bolam and Whomersley, 2005). In other studies, Huxham and Richards (2003) noted a positive correlation between the colonization of *M. balthica* of three sediment treatments and percentage silt/clay and carbon contents, suggesting a preference for areas where both sediment characteristics were high.

The distributions of certain macro-faunal species are significantly correlated with the percentage L.O.I. of the mud treatment and controls. *Hediste diversicolor* was negatively correlated with the mean organic content of the upper-shore mud treatment and controls and the distribution of *R. obtusa* was positively correlated with the organic content of the mud treatment and controls at the high-shore. Other mollusc species distributions were positively correlated to the organic content of the mud treatment and controls of the high-shore (transect 2) such as, *M. balthica* and Tellinacea juveniles. However, the distribution of

M. balthica at the mid-shore was negatively correlated to sediment organic content. The amount of sediment organic content of this study is equal to the high-organic content sediment treatment used by Bolam, *et al.*, (2004) at a mudflat along the Crouch Estuary, although the duration of the present study was shorter in comparison to the Crouch experimental duration of 12 months. Bolam, *et al.*, (2004) noted that the colonization of the sediment treatments by the mobile species *H. diversicolor* and *H. ulvae* were not significantly different in abundance to the mudflat control. They concluded that the most noticeable effects on recovery occurred with an increase of sediment organic content from 0.8 % to 3.4 % and detrimental effects such as delayed recovery of mudflat fauna were experienced during an *in situ* sediment manipulation study. However, following 12 months of burial, manipulated organic content treatments revealed the mudflat faunal community had recovered in a treatment of low-organic content, but had not significantly recovered in the high-organic content treatment (Bolam, *et al.*, 2004). Indeed, Ford, *et al.*, (1999) investigated the effect of buried algal mats on the colonization of the macro-zoobenthos at the intertidal sandflats of Papanui Inlet, Otago Peninsula, New Zealand and noted a change of organic content can cause an increase or decrease of macro-faunal densities. The inhibition of larval settlement to a soft bottom habitat by the presence of negative cues such as algal mats could be a determining factor influencing larval recruitment and distribution (Olafsson, 1988).

4.4.3.3 Sediment sand content

Other sedimentary characteristic can affect macro-faunal recovery and Bolam, *et al.*, (2004) postulated that mudflat faunal recovery was affected by an increased sand content (from 12.0 % to 47.0 %) in the short-term (1 month) but had no detrimental effects on recovery in the long-term. In the present study, the amount of sand content was low (and un-manipulated) and was not significantly correlated to any macro-faunal species distribution when simulated dredged material was placed at the upper-, high- or mid-shore areas and the sediment sand contents of this study were comparable to those used in a study undertaken by Bolam, *et al.*, (2004).

In general, the re-colonization of the mud treatment and defaunated control was high, especially during the initial recovery period and towards the latter stages of the experiment. However, the rate of macro-faunal recovery of the mud treatment and the defaunated control differed between tidal heights. Additionally, the increased water content of a sediment treatment can have a negative affect on the colonization ability of certain mollusc species, such as *M. balthica*, Tellinacea juveniles and *H. ulvae*. Therefore, the tidal height position of a potential recharge area and the fluidity of the recharge sediment may be important factors to consider before the implementation of a dredged material beneficial use scheme takes place. These factors were investigated further in the subsequent chapter.

4.5 Conclusions

1. **Recovery**: Recovery was rapid initially and remained in the opportunist-dominant phase typical of the adjacent mudflat, following the multiple thin depositions of simulated fine-grained dredged material to a total depth of 14 cm over a 17-wk period. The recovery of univariate parameters such as the total individuals and species richness in most instances remained dissimilar to the natural mudflat level and remained significantly different at the high- and mid-shores. The macro-faunal colonization of the upper-shore mud treatment was similar to the natural mudflat level. The community analysis revealed a similarity between the communities of the mud treatment and controls in late April suggesting the initial stages of macro-faunal recovery at the high-shore (transect 2) were similar. Additionally, the recovery of total individuals and species richness differed between tidal heights and were greater at the high-shore when compared to the upper- and mid-shore areas. The mud treatment total individuals biomass was highest at the mid-shore (2.5 g), followed by the high-shore (transect 2) (2.4 g) and the upper-shore (0.8 g). Overall, the high-shore (transect 2) was the most productive in terms of biomass yielded from the mud treatment and defaunated control and reached a combined total of 5.5 g, the mid- and upper-shores combined biomass yields were 4.0 g.
2. **Best colonizer**: *Tubificoides benedii* demonstrated a high ability to colonize an increased water content mud treatment and the defaunated control throughout the experiment at the high-shore (transect 2) and mid-shore but colonized the upper-shore mud treatment and defaunated control from the mid to end period of the experiment.
3. **Upper-shore colonizers**: *Hediste diversicolor*, in particular the juvenile stage and *T. benedii* demonstrated a good ability to colonize the upper-shore mud treatment and defaunated control.
4. **High-shore colonizers**: Early colonizers included *T. benedii* and Nematoda at the high-shore, *M. balthica* colonized the mud treatment and defaunated control throughout the experiment whilst other species colonized the microcosms from July onwards; *T. benedii*, *S. shrubsolii*, *H. ulvae* and *H. diversicolor* (both adult and juveniles).
5. **Mid-shore colonizers**: The early colonizers of the mud treatment and defaunated control were *T. benedii*, *M. balthica*, *P. elegans* and *S. shrubsolii*, followed by nematode colonization mid-way through the experiment and *T. benedii* throughout the experiment.
6. **Macro-fauna x treatment (negative correlations)**: *Macoma balthica* was negatively correlated to the water content of the mud treatment and controls and the ability of *M. balthica* to colonize high-water content (40.0 %) sediments (via settlement) could be negatively affected when deposited at the high- or mid-shore areas. *Hydrobia ulvae* colonization ability was negatively correlated to the water content of sediment when deposited at the upper- and high-shore areas and the colonization ability of juvenile Tellinacea (via settlement) was negatively correlated to the water content of sediment when deposited at the high-shore.
7. A conceptual model of multiple depositions of manipulated sediment was constructed and macro-faunal community response was compared in the general discussion (Chapter 6).

5 Macro-faunal settlement onto two treatment types of simulated dredged material

5.1 Introduction

It is well documented that movement by adult macro-fauna is common in soft sediments and may be a reason for the differences in spatial and temporal variation in abundance resulting in different sized macro-faunal patches of mudflat area. Indeed, a dispersal mechanism to exploit new patch areas may include a combination of active migration with passive drift; for example, an individual may actively swim in the water column and became passively transported with the current before settling onto a new area of mudflat (Andre, *et al.*, 1993; Commito, *et al.*, 1995). The previous chapters have shown that populations can survive under stressed conditions such as burial caused by the deposition of simulated fine-grained dredged material, if individuals successfully migrate through and reach their natural position within the sediment matrix. Similarly, dispersal mechanisms of some mudflat invertebrate species allow opportunistic individuals to exploit new resources such as areas of deposited dredged material used within a beneficial use scheme. For example, important recovery mechanisms include the active migration of individuals via swimming in the water column, settlement of post-juvenile individuals and planktonic settlement of larvae. Once an opportunist species has colonized an area of dredged material deposition, further colonization from within the deposition will occur through the reproduction of immigrants. The dispersal of oligochaete species such as *Tubificoides benedii* (Udekem), *Paranais litoralis* (O.F. Müller) and Enchytraeids are benefitted by characteristics that allow for fast growth and the ability to reproduce asexually.

Diaz, (1994) studied macro-faunal recovery in a freshwater tidal river in Virginia, USA where large quantities of fluid sediment was deposited. Similarly, thin layer fluid sediment depositions were placed during an estuarine field study in New Zealand (Norkko, *et al.*, 2006). Beneficial use of fine-grained dredged sediment has been investigated at several recharge schemes in the UK; this includes the spatial and temporal variation of re-colonizing biota within each scheme (Bolam and Whomersley, 2003; 2005; Bolam, *et al.*, 2006). Sedimentary characteristics of the deposited recharge material was monitored over time, the rapid de-watering of the deposited dredged material slurry which occurred at the Titchmarsh Marina scheme following three months post-recharge was observed by Bolam, *et al.*, (2006). The recharged area of a beneficial use scheme is usually devoid of benthic macro-invertebrates and comprises of sediments with different physico-chemical properties to the surrounding mudflat areas. The deposited dredged material used in beneficial use is often high in water content and placed as slurry. The purpose of this study is to further discern the ability of estuarine macro-fauna to re-colonize a high-water content fine-grained sediment treatment and a lower-water content sediment treatment, via swimming and/or settlement (both actively and passively) from the water column.

5.1.1 Aims, objectives and null hypotheses

Further to the previous years experiment (Chapter 4), an investigation into the temporal variation of invertebrate re-colonization of simulated dredged material through macro-faunal recruitment at three tidal heights the upper-, high- and mid-shore areas was implemented in April 2003. This manipulative field experiment is a continuation from the previous year and included 2 types of fine-grained sediment treatments. This second manipulative field experiment was aimed at improving the ability to predict the affects of changes in sediment water content on estuarine macro-faunal re-colonization of simulated dredged material deposited at different tidal heights of an intertidal mudflat, thereby examining the spatial and temporal variations. The main objectives of the study were to compare (a) univariate community characteristics and (b) species composition of different tidal heights and to determine if an increase in the water content of manipulated sediment treatments influences the re-colonization potential of temperate mudflat macro-fauna. In particular, the following null hypotheses were tested; (a) macro-faunal re-colonization are not affected by changes in water content of simulated fine-grained dredged material and (b) macro-faunal re-colonization is not affected by amount of sediment deposition, (c) macro-faunal re-colonization is not affected by tidal height.

5.1.2 Study experimental site

The experimental site was located at the Skeffling mudflats, along the Humber Estuary, as described in Chapter one.

5.2 Methods and Materials

In order to further examine the relationship between percentage water content and macro-faunal settlement two manipulated fine-grained sediment treatments were used. The sediment collected from the surface layers of the Skeffling mudflats was later defaunated using a freeze-thaw method described previously. The revised methodology was used to simulate the conditions experienced during a recharge scheme. The treatments included a high-water content mud treatment (T1) and a second lower-water content mud treatment (T2) (previously known as treatment 1, 2002) and two controls; a defaunated mudflat control (C1) and a natural mudflat control (C2) (as noted in Chapter 4). Following the defaunation of simulated dredged material and prior to water content manipulation, the surface water was decanted from each 5 l container. The first treatment (T1) contained a mix of 1.5 l of filtered seawater (29) added to 5 l of native defaunated mud to obtain an overall mean water content of 50 % and a mean wet bulk density of 0.68 g cm $^{-3}$. The wet bulk density method was described previously (Chapter 4). The second treatment (T2) contained a mix of 500 ml of filtered seawater added to 5 l of native defaunated mud to obtain an overall mean water content of 40 % and a mean wet bulk density of 1.06 g cm $^{-3}$. The bulk density was similar to the recharge material at two beneficial use schemes (Widdows, *et al.*, 2006). To test the homogeneity of the material, a number of 50 ml sub-samples were randomly removed for further sediment analysis. Following the freeze-thaw process, the defaunated mud used for the control 1 was homogenized and the mean water content of 34 % and the mean wet weight bulk density of 0.92 g cm $^{-3}$ remained un-manipulated. Similarly, the natural mudflat sediment cores had a mean water content of 33 % and a mean wet weight bulk density of 0.91 g cm $^{-3}$. Treatment 2 had slightly higher water content to that of the top surface layers of a typical Skeffling mudflat during 2003. Whilst treatment 1 (50 %) had a similar water content to the fine-grained maintenance dredged material slurry generated during a beneficial use scheme at a North Shotley mudflat, along the Orwell Estuary of 60 % and of the recharge site at the same location of 55 % water content (Bolam & Whomersley, 2004). In order to examine both the rate and the frequency of sediment deposition, 170 ml depositions of each treatment and control 1 were transferred into 200 ml sealed plastic containers and stored in a freezer at – 20 °C. The total volume of material added to gain the required simulation depth per microcosm was calculated as described in Chapter 4.

The experimental sites were located at the upper-shore (53 °N 38.574, 000 °E 04.062), the high-shore (53 °N 38.495, 000 °E 04.055) and the mid-shore areas. At each experimental site, a total of 63 Perspex tubes (10.4 cm id x 35 cm d) including 21 x treatment 1, 21 x treatment 2 and 21 x defaunated control microcosms were placed within a randomised grid block design (1 m^2) (Figure 5.1) to a depth of 15 cm. However, due to time constraints only those samples from the first five sampling occasions were processed for macro-faunal identification. A total of three experimental blocks were set-up at each tidal height, each containing a labelled microcosm replicate of treatment 1 (T1), treatment 2 (T2) and a replicate of defaunated control (C1). Using a core sampler (10.4 cm id x 20 cm d) a second control (C2) was taken from an undisturbed area of mudflat, next to each experimental site, this also provided an indication of the nature of the estuarine benthos.

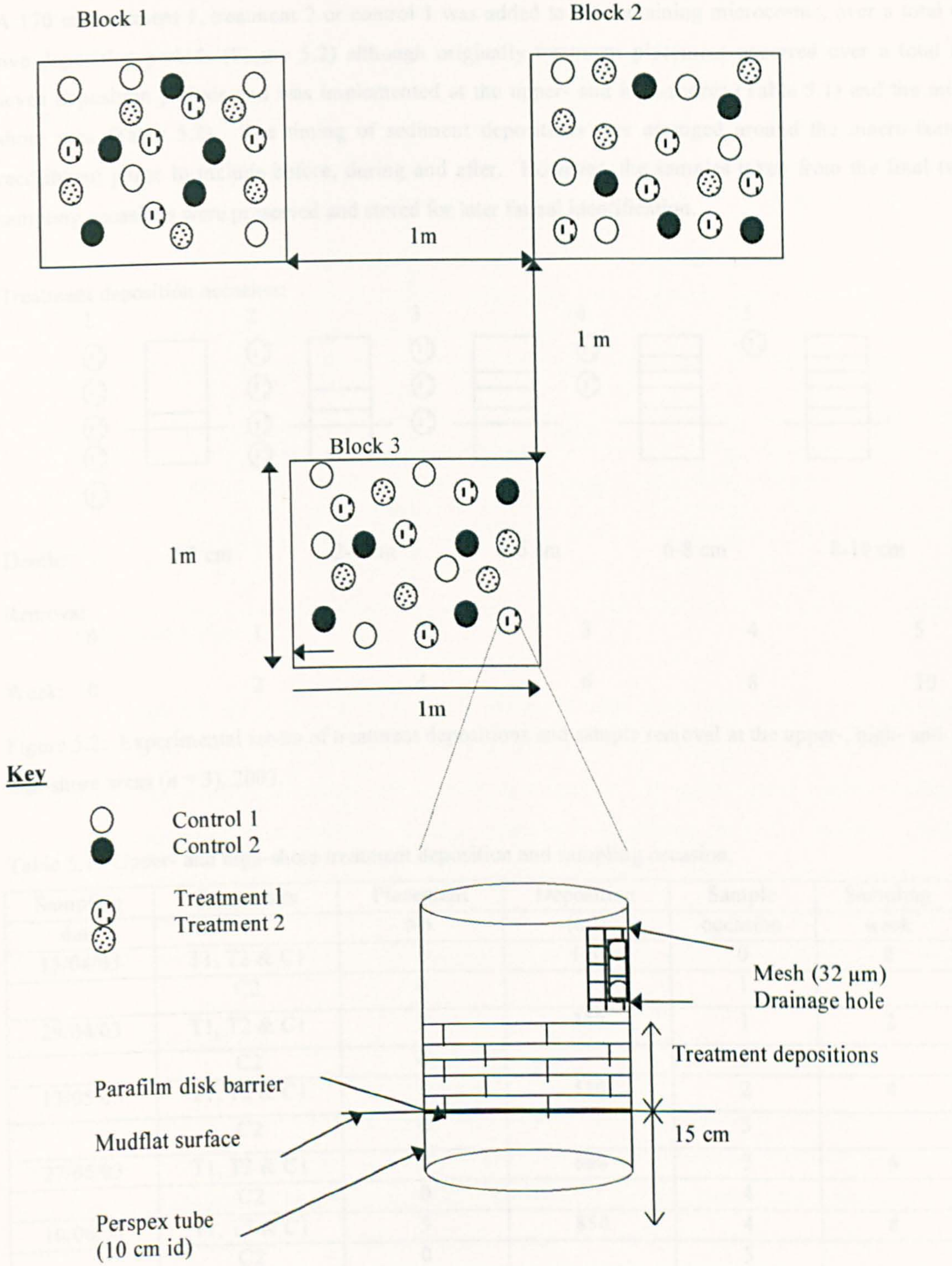


Figure 5.1: Experimental set-up of plots types and core positions (n = 3), 2003.

The drainage holes present on each microcosm, the placement of a Parafilm disk inside each microcosm and the thawing of each sub-sample were the same as described in Chapter 4. At the field site the sub-samples (T1, T2 and C1) were placed into the centre of each microcosm. Thereafter on each sediment deposition occasion, three replicates of control 1, control 2, treatment 1 and treatment 2 were extracted and immediately sectioned into 2 cm increments, thus allowing any macro-fauna settlement to be examined. All 2 cm veneers were preserved *in situ* during each sampling occasion with 4% formo-saline buffered solution with Rose Bengal vital stain to aid extraction of the fauna.

A 170 ml treatment 1, treatment 2 or control 1 was added to the remaining microcosms, over a total of five deposition periods (Figure 5.2) although originally treatment placement occurred over a total of seven deposition periods and was implemented at the upper- and high-shores (Table 5.1) and the mid-shore area (Table 5.2). The timing of sediment depositions was arranged around the macro-faunal recruitment phase to include before, during and after. However, the samples taken from the final two sampling occasions were preserved and stored for later faunal identification.

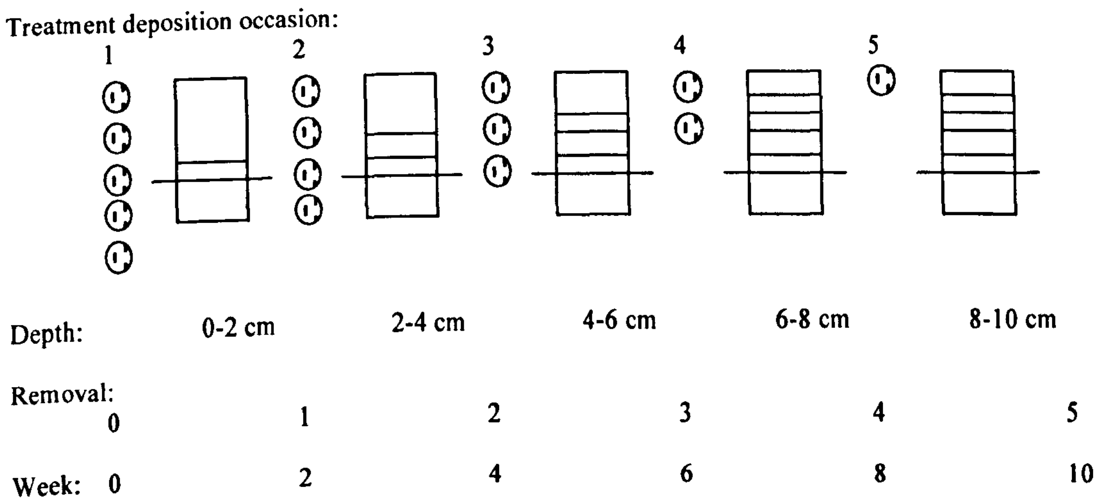


Figure 5.2: Experimental set-up of treatment depositions and sample removal at the upper-, high- and mid-shore areas ($n = 3$), 2003.

Table 5.1: Upper- and high-shore treatment deposition and sampling occasion.

Sampling date	Treatments	Placement No.	Deposition (ml)	Sample occasion	Sampling week
15/04/03	T1, T2 & C1	1	170	0	0
	C2	0		1	
29/04/03	T1, T2 & C1	2	340	1	2
	C2	0		2	
13/05/03	T1, T2 & C1	3	510	2	4
	C2	0		3	
27/05/03	T1, T2 & C1	4	680	3	6
	C2	0		4	
10/06/03	T1, T2 & C1	5	850	4	8
	C2	0		5	
24/06/03	T1, T2 & C1	6	1020	5	10
	C2	0		6	
08/07/03	T1, T2 & C1	7	1190	6	12
	C2	0		7	
22/07/03	T1, T2 & C1	0		7	14
	C2	0		8	

Table 5.2: Mid-shore treatment deposition and sampling occasion.

Sampling date	Treatments	Placement No.	Deposition (ml)	Sample occasion	Sampling week
14/04/03	T1, T2 & C1	1	170	0	0
	C2	0		1	
28/04/03	T1, T2 & C1	2	340	1	2
	C2	0		2	
12/05/03	T1, T2 & C1	3	510	2	4
	C2	0		3	
26/05/03	T1, T2 & C1	4	680	3	6
	C2	0		4	
09/06/03	T1, T2 & C1	5	850	4	8
	C2	0		5	
23/06/03	T1, T2 & C1	6	1020	5	10
	C2	0		6	
07/07/03	T1, T2 & C1	7	1190	6	12
	C2	0		7	
21/07/03	T1, T2 & C1	0		7	14
	C2	0		8	

5.2.1 Faunal analyses

All samples were left for at least 48 h, to allow staining to take place, each sample was then passed through two sieves with a 500 μm and a 125 μm mesh screen, thus separating juveniles from adult macro-fauna and any meio-faunal specimens, and simplifying extraction. All macro-faunal recruits retained on the 125 μm mesh screen were stored in 4 % formo-saline buffered solution for further analysis. All adult macro-fauna retained on the 500 μm mesh screen were sorted using a stereo dissecting microscope and placed into taxonomic groups and stored in 70 % IMS and labelled with the sampling occasion, treatment type, replicate and increment number. Identification and enumeration of all specimens was carried out.

5.2.2 Sediment analysis

Several environmental parameters were measured in order to determine any correlation between these and the biota and between tidal heights. Sub-samples of the controls and treatment sediments were analysed in a Malvern Mastersizer 2000 for particle size distribution to give the median and mean particle grain size, percentage sand and silt/clay fractions. Additionally other sediment parameters such as percentage dry weight; the carbon content was expressed, as the percentage loss on ignition (L.O.I.) and percentage water content were determined. The sediment samples were placed in deep freeze upon return to the laboratory. This was necessary in order to prevent the mineralising effects of microorganisms upon the organic matter present in the sediment and therefore produced data that are more accurate. A 2.5 g sediment sub-sample was weighed once the balance had returned to zero. Each sub-sample was dried for 24 h at 86 ° C and later weighed following cooling and recorded as dry weight. Each sediment sub-sample was placed in a muffle furnace for 4 h at 474 ° C. Ash free dry weight was calculated as described previously and the value for percentage loss on ignition (L.O.I.) was produced. The percentage water content was determined as the wet weight mass subtracted from the dry weight mass.

5.2.3 Data analyses

The invertebrate data were analysed using both univariate and multivariate techniques as described in Chapter 4. The data were checked for normality using the Kolomogrov-Smirnov test and homogeneity of variances were tested using a Levene's test and descriptive statistics were determined. Any data not conforming to a normal distribution were transformed using a square-root transformation (Zar, 1996). As the same plots were sampled throughout the experiment, there was an increased risk of a type I error being committed resulting in the possibility of non-independence occurring during sampling times. To test the effect of treatment and time on community variables and species abundances, repeated measures analysis of variance tests were performed in which treatment and time were within effect factors and tidal height was considered a between effect factor. If Mauchly's test of spherecity was violated then a Greenhouse-Geisser correction factor was applied to that factor during a within effects repeated measures analysis of variance (Field, 2000). Additionally, the data were tested for homogeneity of variances using a Levene's test. A repeated contrast of between effects was conducted to determine which factor differed to another at each time and treatment at each tidal height. Bonferroni multiple comparison tests were performed to investigate any differences between time and between treatments. All univariate analyses were conducted using SPSS version 13.

The Shannon-Wiener index (H') was used to indicate community diversity. This integrates species richness and relative abundance (Barker *et al.*, 1987) and high values indicate high diversity, whilst low values indicate low diversity. Pielou's evenness index (J') was used to give a measure of the relative abundance of each species. A low diversity is expressed as a low J' value and indicates a community is dominated by one or few species, a situation which often occurs in low diversity areas subject to disturbance. A more diverse community were there is an even spread of individuals between the species is expressed as a J' value closer to 1. Both univariate indices (H' and J') were performed using MVSP version 3.12a. Multivariate classification analysis (cluster analysis) of the data was undertaken using the Bray-Curtis similarity coefficient and group average (UPGMA) clustering technique. Cluster analysis was performed on species composition to assess (dis) similarities between community assemblages of the controls and treatments. The similarity between the controls and treatment is calculated using the Bray-Curtis similarity coefficient to produce a similarity matrix showing the percent similarity of groups (0 % indicating no species in common and 100 % indicating an identical community). A dendrogram was used to illustrate the relative importance of controls and the treatment type on community structure, consequently it is possible to define groups of sites with similar species composition at a predefined level of similarity. All multivariate analyses were performed using MVSP version 3.12a.

A Spearman Rank bivariate correlation test was used to determine any links between species abundance and community variables and sediment variables. Principal Components Analysis (PCA) was performed on the sediment variables. Canonical Correspondence Analysis (CCA) a multivariate correlation test was used to determine any relationships between faunal colonization and measured sediment variables, such as percentage water content and percentage silt/clay content. The ordination diagram showed links between individual species and sediment variables.

5.3 Results

5.3.1 Sediment variables 2003

5.3.1.1 Upper-shore controls and treatments

Percentage water content was successfully manipulated to produce two sediment treatments, treatment 1 had a higher mean percentage water content of 49.0 % and silt/clay content of 81.0 % and treatment 2 had a lower mean percentage water content of 39.0 % and silt/clay content of 76.0 % (Figures 5.3 a-b). The defaunated mud control had a similar mean percentage water content to the natural mudflat of the upper-shore (34.0 and 33.0 % respectively). Percentage silt/clay content was high in general and similar throughout the defaunated and mudflat controls with a mean percentage silt/clay content of 75.0 and 74.0 % respectively. The percentage silt/clay content was greater in the treatments when compared to the controls on most sampling occasions except wk 2. Percentage dry weight was greatest in the controls each week and was markedly lower in the treatment 1 (Figure 5.3 c). Percentage loss on ignition (L.O.I.) was similar in the controls on most sampling occasions and % L.O.I. was greater in treatment 1 than the controls during wks 4 to 8 (Figure 5.3 d). The treatments L.O.I. was slightly greater than the controls, for example, ranging from 2.7 to 3.8 % at the upper-shore when compared to the controls (from 2.6 to 3.6 %).

5.3.1.2 High-shore controls and treatments

Percentage water content was greatest in treatment 1, followed by treatment 2 (Figure 5.4 a). The controls had lower percentage water contents of less than 40.0 % and had a similar amount on each sampling occasion except during wk 4 at the high-shore. Percentage silt/clay content was generally high and greater in the treatments when compared to the controls on most occasions except during wk 2 (Figure 5.4 b). Both the controls had the highest percentage dry weight when compared to the treatments (Figure 5.4 c). Treatment 1 had a lower dry weight percentage than the controls and treatment 2 on each sampling occasion. Percentage L.O.I. appeared greater in the treatments (ranging from 2.7 to 4.0 % at the high-shore) when compared to the controls (from 2.7 to 3.6 %) on all sampling occasions except wk 2 (Figure 5.4 d). Overall the sediment variables were similar in the upper- and high-shore experimental blocks.

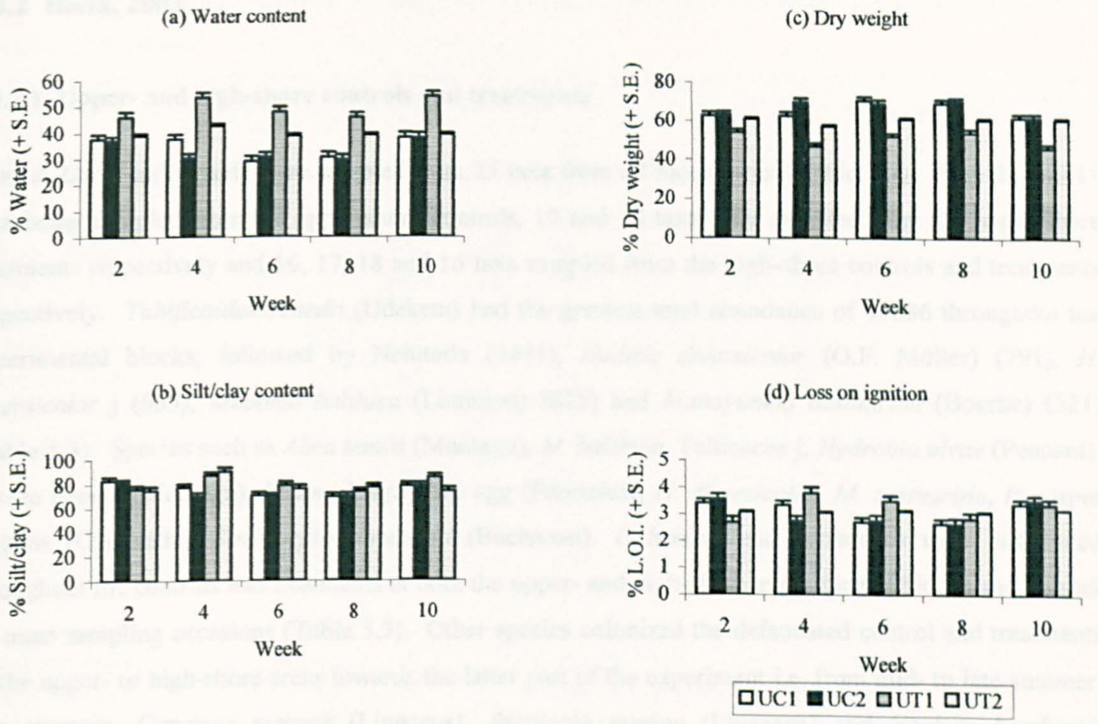


Figure 5.3 (a-d): Changes in upper-shore sediment variables (a) sediment water content, (b) silt/clay content, (c) dry weight content and (d) loss on ignition. Note upper-shore control and treatment abbreviations: defaunated mudflat control (UC1), established mudflat control (UC2), high-water content mud treatment (UT1) and low-water content mud treatment (UT2).

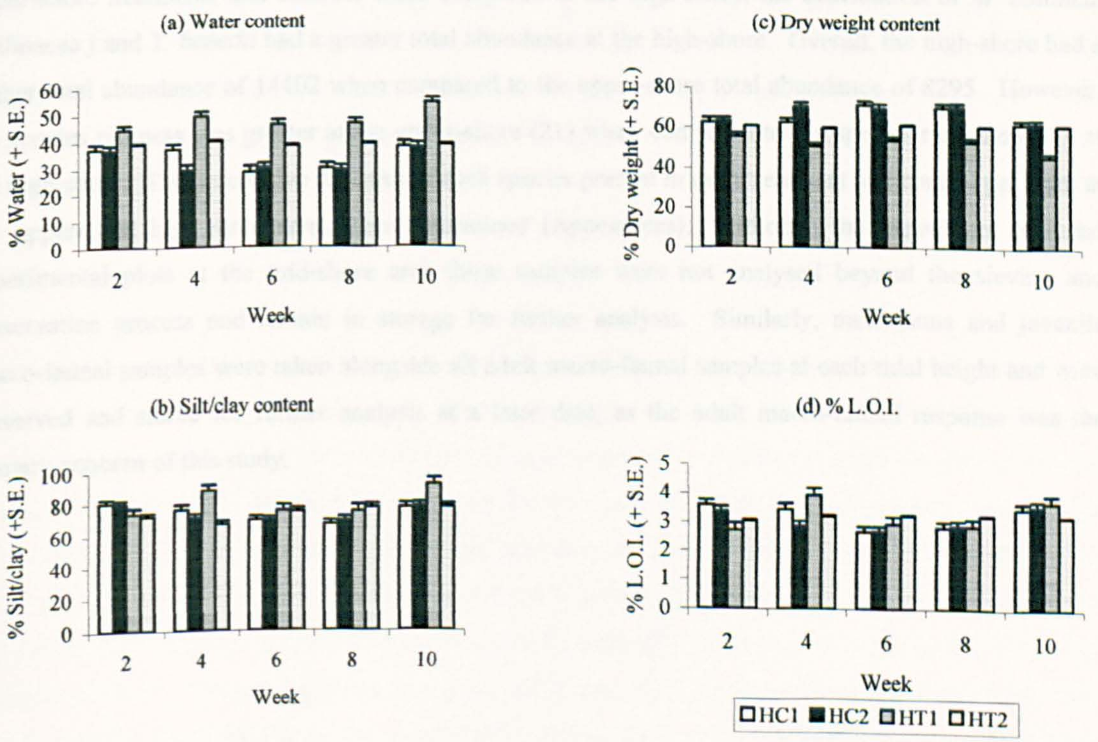


Figure 5.4 (a-d): Changes in high-shore sediment variables (a) sediment water content, (b) silt/clay content, (c) dry weight content and (d) loss on ignition. Note high-shore control abbreviations: defaunated mudflat control (HC1), established mudflat control (HC2), high-water content mud treatment (HT1) and low-water content mud treatment (HT2).

5.3.2 Biota, 2003

5.3.2.1 Upper- and high-shore controls and treatments

In total 22697 individuals were sampled from 25 taxa from all block types (Table 5.3). With 21 and 17 taxa being sampled from the upper-shore controls, 19 and 16 taxa were sampled from the upper-shore treatments respectively and 16, 17, 18 and 16 taxa sampled from the high-shore controls and treatments respectively. *Tubificoides benedii* (Udekem) had the greatest total abundance of 13886 throughout the experimental blocks, followed by Nemtoda (1441), *Hediste diversicolor* (O.F. Müller) (791), *H. diversicolor* j (665), *Macoma balthica* (Linnaeus) (625) and *Manayunkia aestuarina* (Bourne) (521) (Table 5.3). Species such as *Abra tenuis* (Montagu), *M. balthica*, Tellinacea j, *Hydrobia ulvae* (Pennant), *Retusa obtusa* (Montagu), *Eteone longa/flava* agg (Fabricius), *H. diversicolor*, *M. aestuarina*, *Pygospio elegans* (Claparède), *Streblospio shrubsolii* (Buchanan), *T. benedii* and nematodes were distributed throughout the controls and treatments at both the upper- and high-shore experimental blocks and present on most sampling occasions (Table 5.3). Other species colonized the defaunated control and treatments of the upper- or high-shore areas towards the latter part of the experiment i.e. from mid- to late-summer. For example, *Carcinus maenas* (Linnaeus), *Arenicola marina* (Linnaeus) and *Nephyts hombergii* (Savigny) at the high-shore and *Capitella capitata* complex, *Pholoe inornata* (Johnston) and *Polydora cornuta* (Bosch) at the upper-shore. Oligochaete species such as *Paranais litoralis* (O.F. Müller) and Enchytraeidae were present during most weeks of the experiment at the upper-shore only. Species such as *H. ulvae*, *M. aestuarina*, *P. elegans*, *P. litoralis* and Enchytraeidae had a higher total abundance at the upper-shore treatments and controls when compared to the high-shore, the distribution of *M. balthica*, Tellinacea j and *T. benedii* had a greater total abundance at the high-shore. Overall, the high-shore had a higher total abundance of 14402 when compared to the upper-shore total abundance of 8295. However, the species richness was greater at the upper-shore (21) when compared to the species richness of 19 at the high-shore. The descriptive statistics of each species present in each treatment and control per layer at the upper- and high-shore areas were determined (Appendices). Although the experiment included experimental plots at the mid-shore area these samples were not analysed beyond the sieving and preservation process and remain in storage for further analysis. Similarly, meio-fauna and juvenile macro-faunal samples were taken alongside all adult macro-faunal samples at each tidal height and were preserved and stored for further analysis at a later date, as the adult macro-faunal response was the primary concern of this study.

Table 5.3: Taxa in each treatment per sampling occasion at the upper- and high-shores 2003 and the total number of individuals.

	UC1*	UC2	UT1*	UT2*	U total	HC1*	HC2	HT1*	HT2*	H total	Total (n)
Edwarsia		4			1					0	1
Carcinus maenas					0	3	3	5		8	8
Carcinus maenas j					0	5				1	1
Abra tenuis			1-4		12	1-2, 4	1-2, 4	1-2	1-3	32	44
Macoma balthica	1-4	1, 3-5	1-5	2, 4-5	93	1-5	1-5	1-5	1-5	526	619
Tellinacea j	1-4	1, 3-5	2, 4-5	1-2	76	1-2, 5	1-2, 4	1-2, 4-5	1-4	294	370
Hydrobia ulvae	1-4	1-5	1-5	1-2, 4-5	83	2-3	1-2, 4-5	2	2-3, 5	25	108
Retusa obtusa		3-5	1		4	3	1-2, 4-5	1-3	1, 3	41	45
Limpontia depressa	1-2	1	1-2	1	13		2, 4	2		7	20
Arenicola marina					0				4	1	1
Capitella complex agg		4			4					0	4
Eteone longa/flava agg	1, 3-4	1, 3-5	3	2	35	5	1-2, 4-5	3-4		24	59
Hediste diversicolor	2-5	2-5	2-5	2-5	384	1-5	3-5	2-5	2-5	407	791
Hediste diversicolor j	1-4	1-5	1-5	1-5	344	2-5	2-3	1-5	1-5	302	646
Manayunkia aestuarina	1-4	1-5	1-5	1-5	487	2-3	1-2, 4-5	1-3	1-2	34	521
Nephyts hombergii					0			5	3	2	2
Pholoe inornata		3			1					0	1
Polydora cornuta		4-5	5		8					0	8
Pygospio elegans	1-5	1-5	1-5	1-5	302	1-2, 4-5	1-2, 4-5	1-5	1-4	158	460
Streblospio shrubsolii	1-4	1, 3-5	2-4	1-2, 5	150	1-5	1-5	1-5	1-4	208	358
Tharyx "A"	2	5	4	2	8	1-3, 5	1-2, 4	2-5	1-4	45	53
Tubificoides benedii	1-5	1-5	1-5	1-5	2110	1-5	1-5	1-5	1-5	11480	13590
Paranais litoralis	1-3	1-4	1, 3	1-4	345					0	345
Enchytraeidae	1-5	1-5	1-5	1-5	3170		5			17	3187
Nemertea					0			5	5	2	2
Nematoda	1-5	1-5	1-5	1-4	653	1-5	1-5	1-5	1-5	788	1441
Diptera larvae	3, 5	1-2, 4	1	3	12					0	12
Total number of species	17	21	19	16	21	16	17	18	16	19	

1 indicates the presence in that treatment after 2 wks, 2=4 wks, 3=6 wks, 4=8 wks, 5=10 wks. The total number of individuals sampled of each taxa throughout the experiment is given in the last column. * Disk present between the mudflat surface and treatment deposition. Refer to Figures 5.3 & 5.4 for control and treatment abbreviations.

5.3.2.1.1 Univariate community indices of the upper-shore controls and treatments

The mudflat control of the upper-shore had the highest abundance of individuals each week except wk 2 when treatment 2 was greatest (Figure 5.5a). Similarly treatment 1 had a greater abundance of individuals each week except wk 2 when compared to treatment 2. Treatment 2 had the greatest amount of colonization initially. The initial colonization of the treatments at the upper-shore were less than the defaunated control with 7 and 8 species present in treatments 1 and 2 respectively when compared to 11 and 7 species in the defaunated and mudflat controls respectively (Figure 5.5b). The number of species colonizing the treatments increased from wks 4 to 8, especially those present in treatment 1 but later declined at wk 10. The species richness of the mudflat control of the upper-shore increased by wk 6 and was highest for the remainder of the experiment. Overall species diversity was greatest in the mudflat control apart from wk 4 when treatment 2 was higher (Figure 5.5c). Species diversity in the treatments was low initially but increased by wk 4. Diversity was greater in treatment 1 when compared to treatment

2 during wks 6 to 8. The value of Pielou's evenness varied each week but followed a similar pattern to the Shannon-Wiener diversity mention earlier (Figure 5.5d).

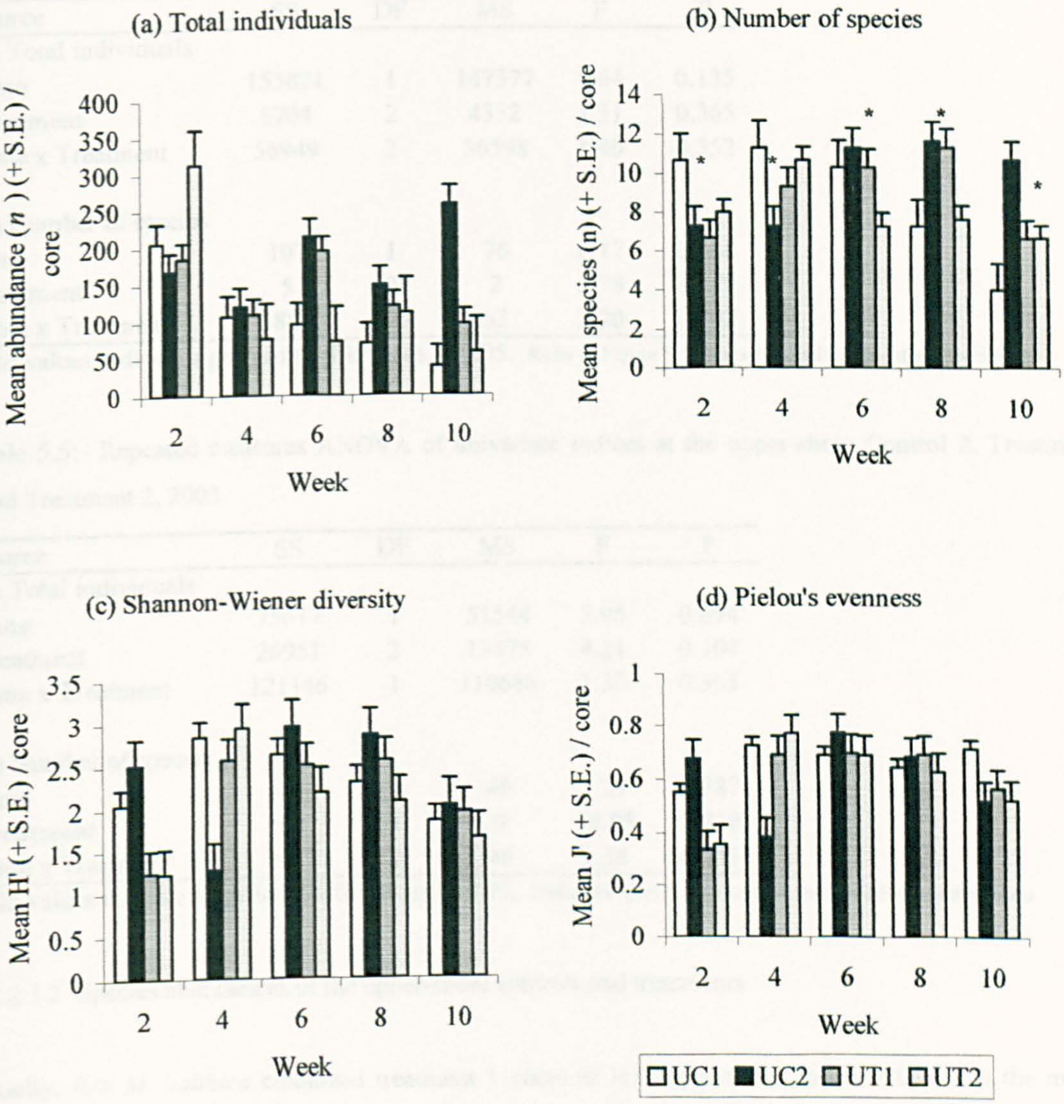


Figure 5.5 (a-d): Univariate parameters for each station at the upper-shore per core per sampling occasion (+ S.E., n=3). * Denotes a repeated contrast significant difference to the mudflat control (C2). Refer to Figure 5.3 for control and treatment abbreviations.

The abundance of total individuals and species richness at the upper-shore were not significantly different between treatments or time when comparing the defaunated control and treatment 1, followed by the defaunated control and treatment 2 (Table 5.4). The treatment type significantly differed when comparing the species richness of the mudflat control with treatments 1 and 2 (Table 5.5) (Figure 5.5). Repeated contrasts revealed significant interactions between time and treatment however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Tables 5.4 and 5.5).

Table 5.4: Repeated measures ANOVA of univariate indices at the upper-shore Control 1, Treatment 1 and Treatment 2, 2003.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time	155821	1	147377	5.64	0.135
Treatment	8704	2	4352	1.31	0.365
Time x Treatment	56949	2	36598	1.40	0.352
(b) Number of species					
Time	107	1	76	8.17	0.068
Treatment	5	2	2	2.78	0.175
Time x Treatment	88	2	52	2.20	0.242

Bold values indicate significant differences, $p<0.05$. Refer to Figure 5.3 for control and treatment abbreviations.

Table 5.5: Repeated measures ANOVA of univariate indices at the upper-shore Control 2, Treatment 1and Treatment 2, 2003.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time	75617	1	51544	5.95	0.094
Treatment	26951	2	13475	4.21	0.104
Time x Treatment	121146	1	110688	1.35	0.365
(b) Number of species					
Time	48	1	46	1.21	0.387
Treatment	**18**	**2**	**9**	**18.05**	**0.010**
Time x Treatment	91	2	46	1.38	0.351

Bold values indicate significant differences, $p<0.05$. Refer to Figure 5.3 for control and treatment abbreviations.

5.3.2.1.2 Species abundances of the upper-shore controls and treatments

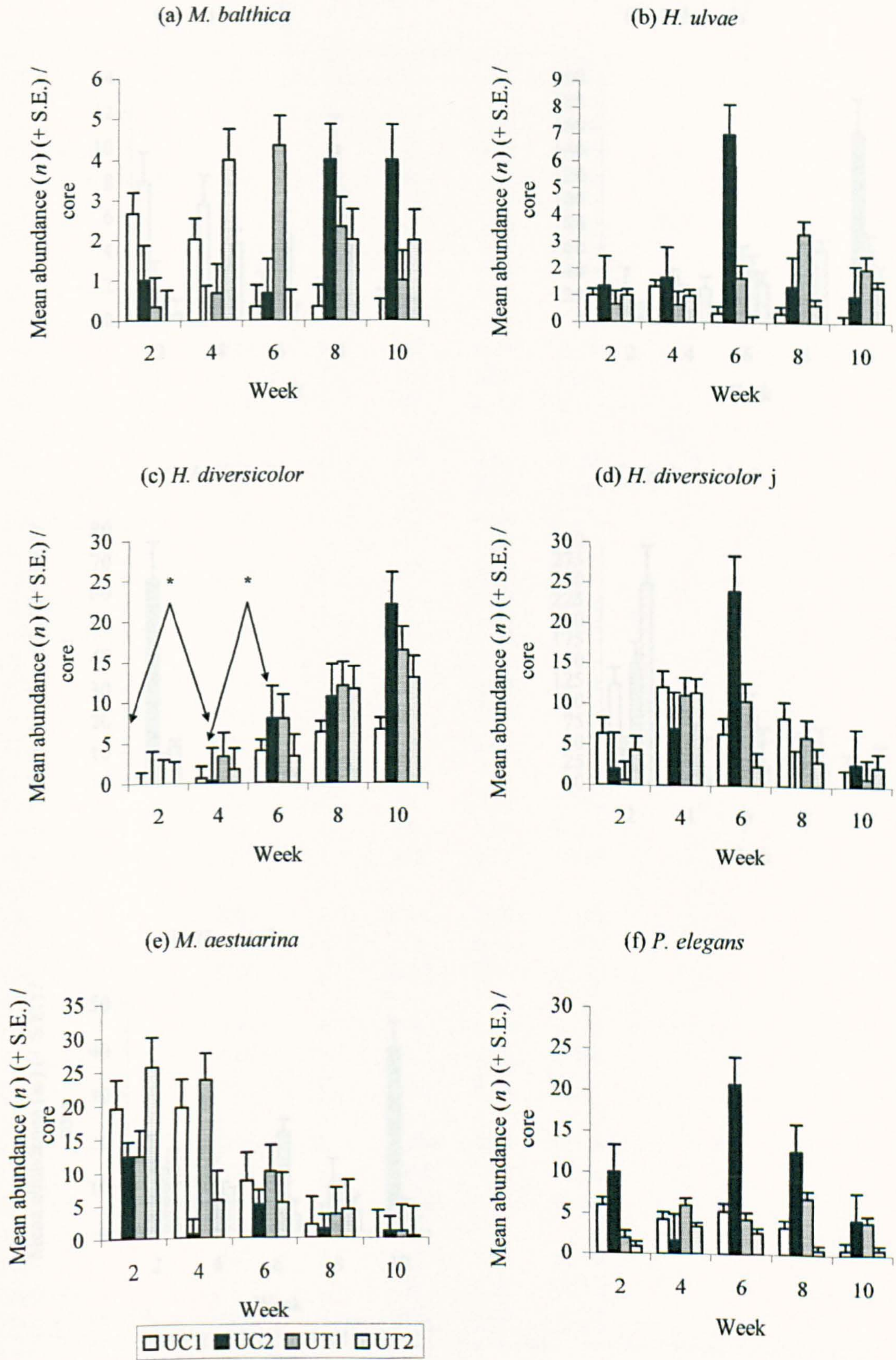
Initially, few *M. balthica* colonized treatment 1 cores of the upper-shore however by wk 6 the mean abundance had increased (Figure 5.6a), some colonization of the treatments occurred between wks 4 and 10 but low numbers occurred overall. Similarly, low counts of *H. ulvae*, *S. shrubsolii* and *P. litoralis* occurred (Figures 5.6 b, g and i). A gradual increase of mean abundance of *H. diversicolor* and *T. benedii* occurred from wks 2 to 10 in the defaunated control and treatments and was equal to or higher than the mudflat levels from wks 2 to 8. However, by wk 10 the mudflat control was highest (Figures 5.6 c and h). Initially *H. diversicolor* j quickly colonized the treatments and defaunated control with a peak attained by wks 4 to 6, colonization subsequently decreased towards the latter part of the experiment (Figure 5.6 d). Furthermore, *H. diversicolor* j mean abundance was greater in the treatments and defaunated control each week except wk 6 when an increase of mean abundance occurred in the mudflat control. *Manayunkia aestuarina* mean abundance was higher in the treatments each week when compared to the mudflat control, however colonization decreased over time (Figure 5.6 e). Some *P. elegans* colonization of the treatments occurred especially in treatment 1 at wk 4. However, the mean abundance was highest in the mudflat control on all other sampling occasions (Figure 5.6 f). Enchytraeidae abundance was high initially in the treatments, especially treatment 2. However, by wk 6 treatment 1 was higher, a general decrease in treatment colonization occurred thereafter (Figure 5.6 j).

Similarly, nematodes displayed some initial colonization of the treatments especially in treatment 2 however; by wk 6 treatment 1 was higher, followed by a decrease of treatment colonization, by wk 10 the mudflat control colonization increased (Figure 5.6 k).

Mean abundances of all species in the defaunated control and treatments of the upper-shore were not significantly different between time, treatments or an interaction of time x treatment (Table 5.6). *Hediste diversicolor* and *T. benedii* mean abundances were significantly different between time and *P. elegans* significantly differed between treatments when comparing the mudflat control and treatments of the upper-shore (Table 5.7). All remaining species present in the mudflat control and treatments of the upper-shore were not significantly different between the factors. Repeated contrasts revealed a significant difference between time when comparing *H. diversicolor* mean abundance in the mudflat control and the treatments during wks 2 and 4 and wks 4 with 6, additionally a significant interaction between time x treatment occurred and the colonization of the mudflat control differed to the treatment 1 during wks 2 and 4 (Appendix 2 Table 5.7) and a gradual increase of *H. diversicolor* colonization occurred throughout the controls and treatments during the experiment, especially in treatment 1 (Figure 5.6c). Further repeated contrasts revealed significant interactions between time and treatments however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Tables 5.6 and 5.7).

5.3.2.1.3 Similarity in community composition of the upper-shore controls and treatments

The community structure in each treatment and control communities at the upper-shore were divided into two groups, one formed by all of wk 10 treatments and controls followed by wk 8 treatments, treatment 2 and the defaunated control from wks 6 and 4 (Figure 5.7). The second group consisted of all wk 2 treatments and controls, wk 8 controls, treatment 1 and the mudflat control from wks 6 and 4.


(a) M. balthica
(b) H. ulvae
(c) H. diversicolor
(d) H. diversicolor j
(e) M. aestuarina
(f) P. elegans
Mean abundance (n) (+ S.E.) / core
Week
*
UC1 UC2 UT1 UT2

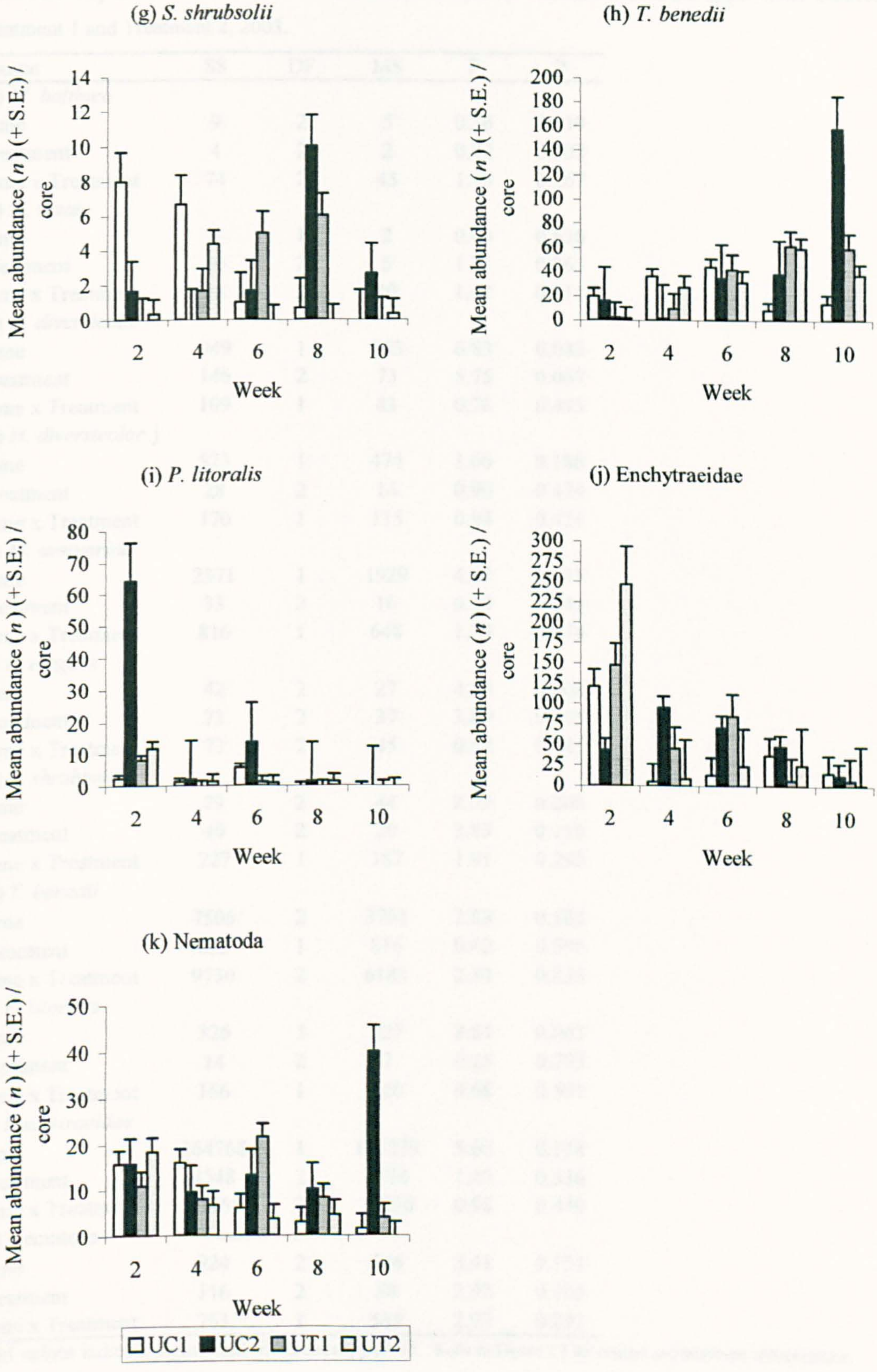


Figure 5.6 (a-k): Mean densities per core per sampling occasion of common taxa at the upper-shore (mean + S.E., n=3). * Denotes a repeated contrast significant difference to the mudflat control (C2). Refer to Figure 5.3 for control and treatment abbreviations.

Table 5.6: Repeated measures ANOVA of abundance data for common taxa at the upper-shore Control 1, Treatment 1 and Treatment 2, 2003.

Source	SS	DF	MS	F	P
(a) *M. balthica*					
Time	9	2	5	0.56	0.610
Treatment	4	2	2	0.82	0.502
Time x Treatment	74	2	45	1.98	0.267
(b) *H. ulvae*					
Time	3	1	2	0.40	0.630
Treatment	10	2	5	1.31	0.365
Time x Treatment	18	2	10	1.62	0.311
(c) *H. diversicolor*					
Time	949	1	663	6.83	0.083
Treatment	146	2	73	5.75	0.067
Time x Treatment	109	1	83	0.76	0.493
(d) *H. diversicolor* j					
Time	523	1	474	3.66	0.186
Treatment	28	2	14	0.90	0.474
Time x Treatment	170	1	115	0.94	0.451
(e) *M. aestuarina*					
Time	2371	1	1929	4.82	0.137
Treatment	33	2	16	0.18	0.845
Time x Treatment	816	1	648	1.29	0.374
(f) *P. elegans*					
Time	42	2	27	4.89	0.108
Treatment	73	2	37	3.89	0.115
Time x Treatment	73	2	45	0.67	0.545
(g) *S. shrubsolii*					
Time	79	2	44	2.59	0.200
Treatment	40	2	20	3.83	0.118
Time x Treatment	227	1	187	1.91	0.292
(h) *T. benedii*					
Time	7506	2	3761	2.68	0.183
Treatment	853	1	816	0.42	0.590
Time x Treatment	9730	2	6183	2.34	0.233
(i) *P. litoralis*					
Time	326	1	227	8.61	0.063
Treatment	14	2	7	0.25	0.793
Time x Treatment	166	1	160	0.68	0.501
(j) *Enchytraeidae*					
Time	164768	1	145279	5.60	0.128
Treatment	4548	2	2274	1.45	0.336
Time x Treatment	35464	2	19230	0.98	0.449
(k) Nematoda					
Time	924	2	546	3.41	0.154
Treatment	116	2	58	2.92	0.165
Time x Treatment	763	1	565	2.97	0.201

Bold values indicate significant differences, $p < 0.05$. Refer to Figure 5.3 for control and treatment abbreviations.

Table 5.7: Repeated measures ANOVA of abundance data for common taxa at the upper-shore Control 2, Treatment 1 and Treatment 2, 2003.

Source	SS	DF	MS	F	P
(a) *M. balthica*					
Time	28	1	24	0.63	0.529
Treatment	1	2	0	0.14	0.874
Time x Treatment	82	2	42	1.45	0.336
(b) *H. ulvae*					
Time	21.9111	4	5	2	0.22
Treatment	22.5778	2	11	2	0.22
Time x Treatment	73.4222	1	49	2	0.27
(c) *H. diversicolor*					
Time	**1781**	**1**	**1775**	**20.12**	**0.046**
Treatment	46	2	23	0.52	0.629
Time x Treatment	138	2	86	0.51	0.605
(d) *H. diversicolor* j					
Time	791	2	527	1.66	0.312
Treatment	63	1	62	0.87	0.449
Time x Treatment	744	1	561	1.77	0.304
(e) *M. aestuarina*					
Time	1416	1	996	2.79	0.208
Treatment	290	2	145	1.67	0.297
Time x Treatment	1007	1	730	1.33	0.366
(f) *P. elegans*					
Time	238	1	171	1.29	0.374
Treatment	**516**	**2**	**258**	**8.02**	**0.040**
Time x Treatment	493	2	274	2.28	0.227
(g) *S. shrubsolii*					
Time	123	1	100	0.92	0.449
Treatment	38	2	19	6.46	0.056
Time x Treatment	199	1	172	1.12	0.403
(h) *T. benedii*					
Time	**36467**	**2**	**19519**	**13.94**	**0.019**
Treatment	2846	2	1423	0.68	0.557
Time x Treatment	24546	2	14915	4.97	0.102
(i) *P. litoralis*					
Time	5041	1	5037	1.64	0.329
Treatment	1845	2	922	0.98	0.452
Time x Treatment	4366	1	4177	0.76	0.479
(j) *Enchytraeidae*					
Time	102460	1	76269	8.58	0.069
Treatment	367	2	183	0.12	0.891
Time x Treatment	82204	1	69638	1.78	0.307
(k) Nematoda					
Time	444	2	257	1.41	0.349
Treatment	956	2	478	5.27	0.076
Time x Treatment	2588	2	1369	2.39	0.213

Bold values indicate significant differences, $p<0.05$. Refer to Figure 5.3 for control and treatment abbreviations.

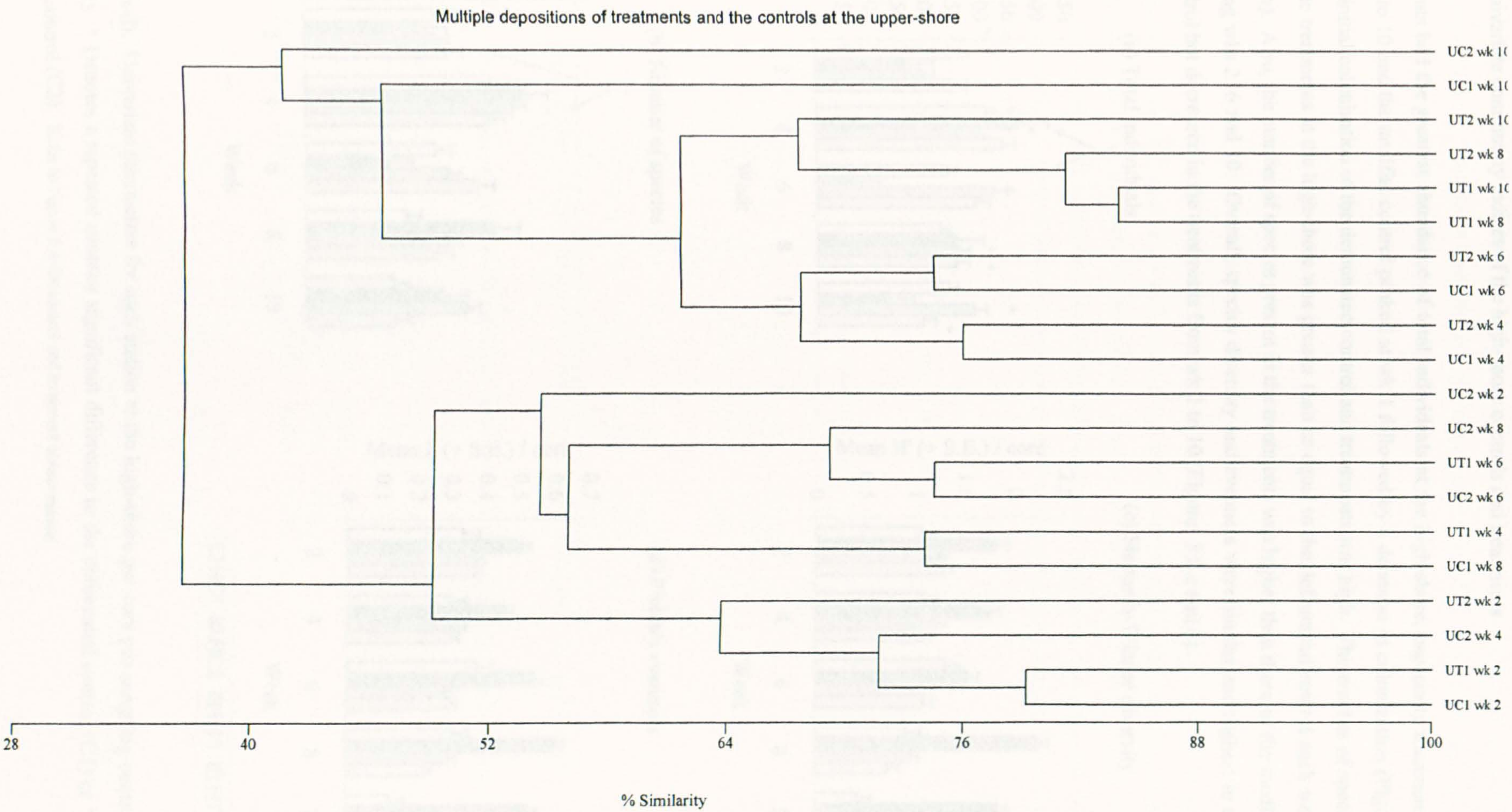


Figure 5.7: Assemblage composition similarity dendrogram of treatment type and sampling occasion at the upper-shore, 2003.

5.3.2.1.4 Univariate community indices of the high-shore controls and treatments

The treatments had the greatest abundance of total individuals at the high-shore, especially treatment 1 from wks 6 to 10 and the mudflat control peaked at wk 4 followed by a decrease in colonization (Figure 5.8 a). The initial colonization of the defaunated control and treatments was high. The number of species present in the treatments at the high-shore was greater than or equal to the defaunated control each week (Figure 5.8 b). Also, the number of species present in the treatments was higher than those of the mudflat control during wks 2, 6 and 10. Overall, species diversity and evenness were similar and highest in the mudflat control but decreased in the treatments from wk 2 to 10 (Figures 5.8 c and d).

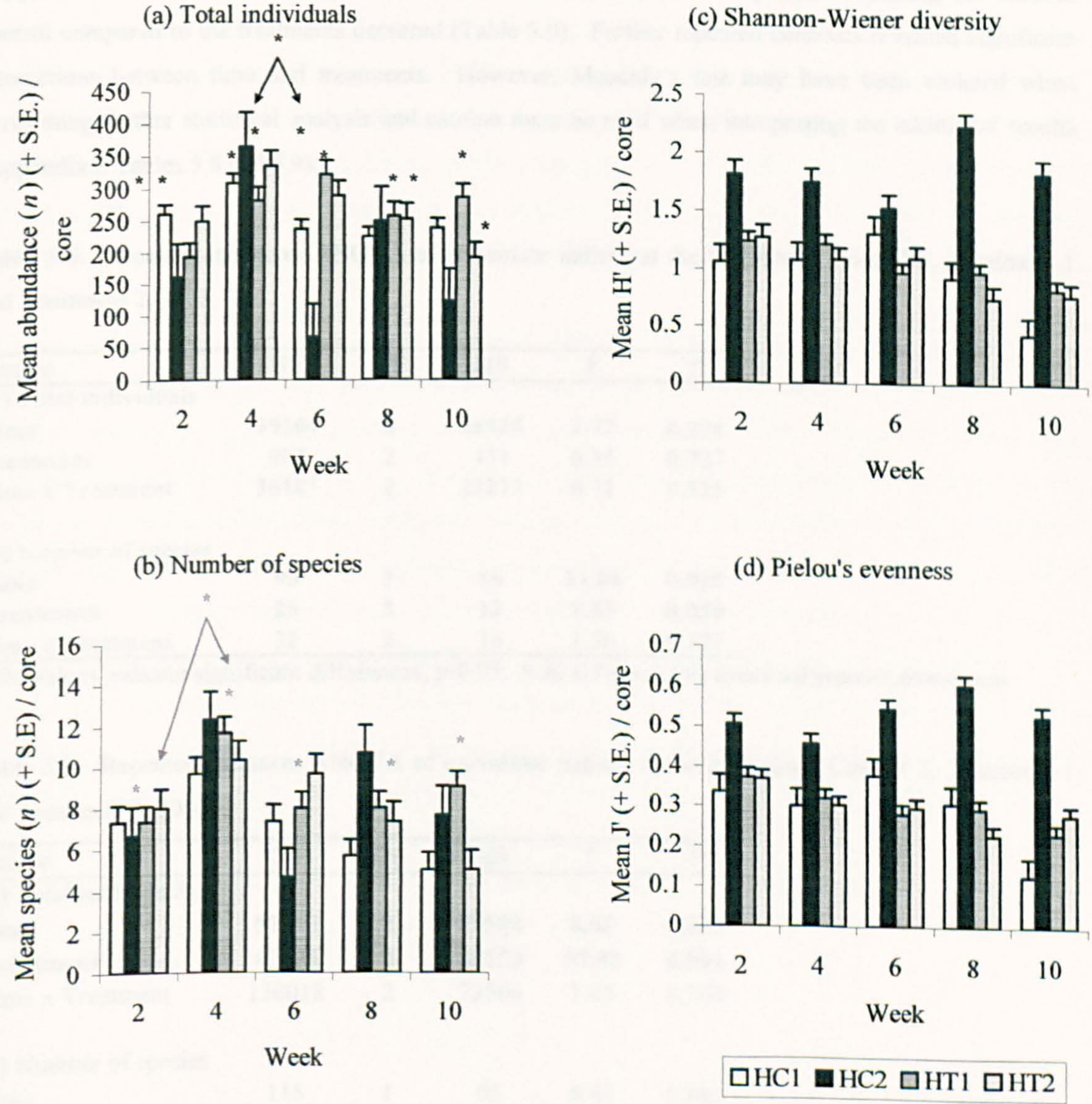


Figure 5.8 (a-d): Univariate parameters for each station at the high-shore per core per sampling occasion (+ S.E., n=3). * Denotes a repeated contrast significant difference to the defaunated control (C1) or * to the mudflat control (C2). Refer to Figure 5.4 for control and treatment abbreviations.

The abundance of total individuals at the high-shore was not significantly different between treatments or time when comparing the defaunated control with the treatments (Table 5.8). However, the species richness at the high-shore significantly differed between treatments and time when comparing the defaunated control with the treatments (Table 5.8) further repeated contrasts showed a significant difference in colonization of the defaunated control and treatment 1 between wks 2 to 4 (Appendix 2 Table 5.8). Additionally, the abundance of total individuals was significantly different between treatments and time when comparing the mudflat control and treatments from wks 2 to 10 (Table 5.9). Further repeated contrasts of treatments and time also showed a significant difference between the total individuals present in mudflat control and treatments and a significant difference between wks 4 and 6 (Appendix 2 Table 5.9). No significant difference in the number of species colonizing the mudflat control compared to the treatments occurred (Table 5.9). Further repeated contrasts revealed significant interactions between time and treatments. However, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Tables 5.8 and 5.9).

Table 5.8: Repeated measures ANOVA of univariate indices at the high-shore Control 1, Treatment 1 and Treatment 2, 2003.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time	39164	2	24428	1.77	0.294
Treatment	903	2	451	0.35	0.727
Time x Treatment	36181	2	23273	0.71	0.525
(b) Number of species					
Time	**95**	**1**	**66**	**21.06**	**0.020**
Treatment	**25**	**2**	**12**	**9.53**	**0.030**
Time x Treatment	32	2	16	1.50	0.327

Bold values indicate significant differences, $p < 0.05$. Refer to Figure 5.4 for control and treatment abbreviations.

Table 5.9: Repeated measures ANOVA of univariate indices at the high-shore Control 2, Treatment 1 and Treatment 2, 2003.

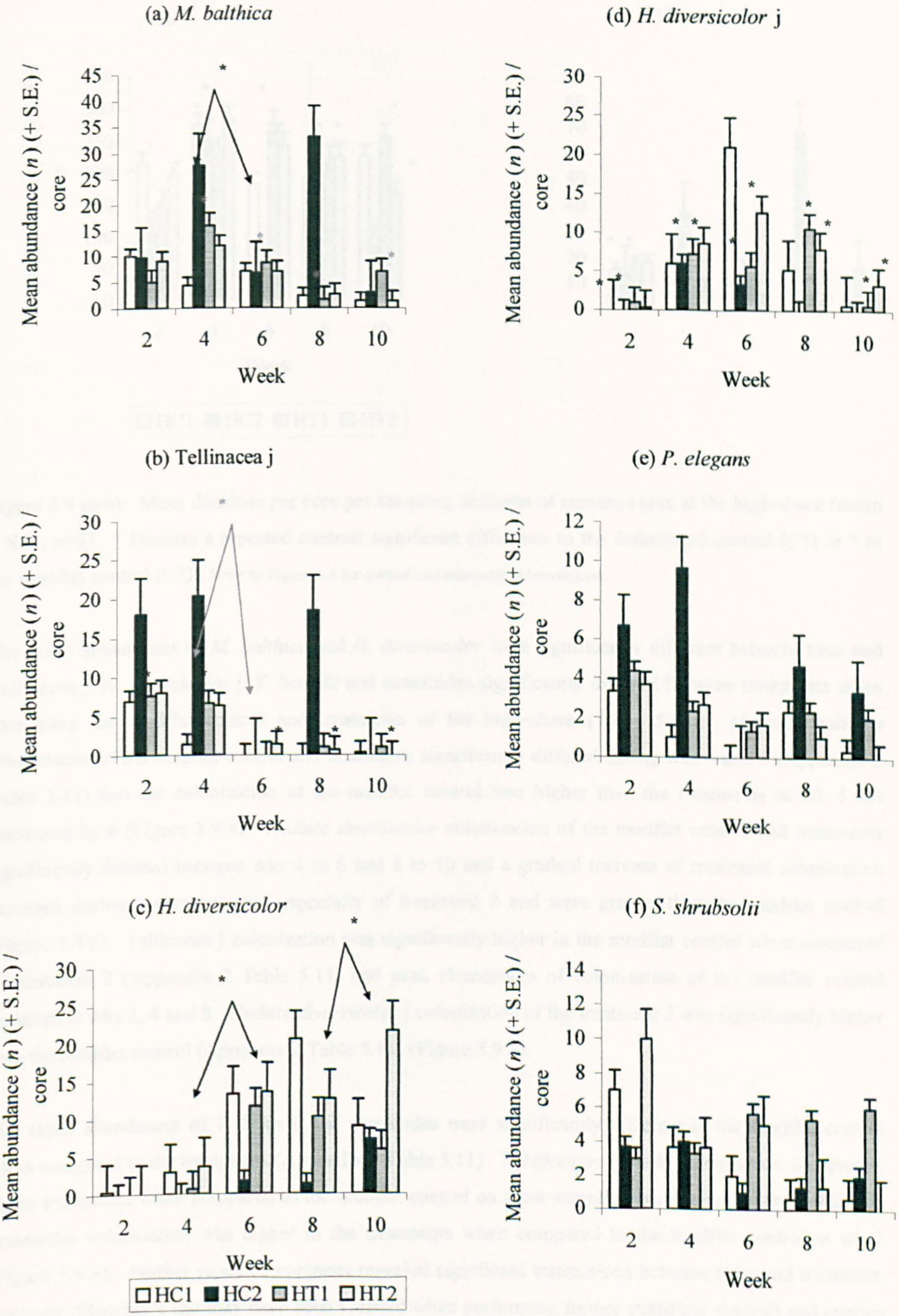
Source	SS	DF	MS	F	P
(a) Total individuals					
Time	**97275**	**2**	**59598**	**8.68**	**0.051**
Treatment	**47105**	**2**	**23553**	**57.92**	**0.001**
Time x Treatment	130018	2	72766	1.45	0.339
(b) Number of species					
Time	115	1	95	8.43	0.081
Treatment	4	2	2	1.57	0.314
Time x Treatment	87	1	61	2.78	0.208

Bold values indicate significant differences, $p < 0.05$. Refer to Figure 5.4 for control and treatment abbreviations.

5.3.2.1.5 Species abundances of the high-shore controls and treatments

Macoma balthica colonization of the defaunated control and treatments occurred throughout the experiment and the colonization of the treatments exceeded the mudflat control on all sampling occasions except wks 4 and 8 (Figure 5.9 a). Juvenile Tellinacea colonization of the treatments was similar each week, although the mudflat control was higher in abundance when compared to the treatments and defaunated control at wks 2, 4 and 8 (Figure 5.9 b). *Hediste diversicolor* colonization increased from wk 2 to 10 and was especially high in the treatments or the defaunated control on each sampling occasion (Figure 5.9 c). Juvenile *H. diversicolor* colonized the treatments and defaunated control more than the mudflat control each week (Figure 5.9 d). Few *P. elegans* individuals colonized the treatment and defaunated control of the high-shore experimental blocks (Figure 5.9 e). Some *S. shrubsolii* individuals colonized the treatments and defaunated control and were generally higher than the mudflat control apart from wk 4 (Figure 5.9 f). Overall *T. benedii* colonization of the treatments was greater than the mudflat controls during wks 2 to 10 (Figure 5.9 g). Some colonization by nematodes occurred initially and was highest in the treatments when compared to the controls during wks 2 and 6. However, the mudflat control abundance was greatest during wks 4, 8 and 10 (Figure 5.9 h).

Macoma balthica mean abundance was significantly different between treatments when comparing the defaunated control and treatments but not significantly different over time (Table 5.10). Further repeated contrasts showed a significant difference between the colonization of the defaunated control and treatment 1 (Appendix 2 Table 5.10). Juvenile Tellinacea and *H. diversicolor* colonization of the defaunated control and treatments significantly differed over time (Table 5.10) and repeated contrasts showed a significant difference of Tellinacea j colonization between wks 4 and 6 and a significant difference of *H. diversicolor* j between wks 2 with 4 and 8 with 10. The mean abundance of Tellinacea j decreased from wks 4 to 6 in all treatments and controls (Figure 5.9 b) and the colonization of *H. diversicolor* j increased from wks 2 to 4 but later decreased from wks 8 to 10 in the treatments (Figure 5.9 d). *Hediste diversicolor, P. elegans, S. shrubsolii, T. benedii* and nematodes were not significantly different between treatments, time or an interaction of time x treatment (Table 5.10). Further repeated contrasts revealed significant interactions between treatment and time. However, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Table 5.10).


(a) M. balthica
(d) H. diversicolor j
(b) Tellinacea j
(e) P. elegans
(c) H. diversicolor
(f) S. shrubsolii
Mean abundance (n) (+ S.E.) / core
Week
2
4
6
8
10
HC1
HC2
HT1
HT2

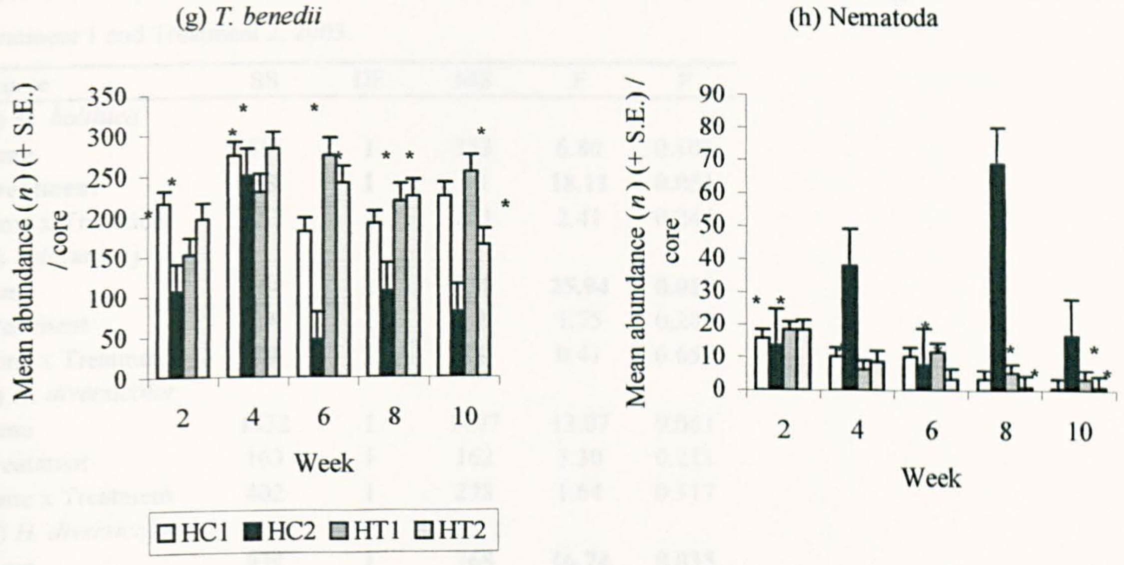


Figure 5.9 (a-h): Mean densities per core per sampling occasion of common taxa at the high-shore (mean + S.E., n=3). * Denotes a repeated contrast significant difference to the defaunated control (C1) or * to the mudflat control (C2). Refer to Figure 5.4 for control and treatment abbreviations.

The mean abundances of *M. balthica* and *H. diversicolor* were significantly different between time and Tellinacea j, *H. diversicolor* j, *T. benedii* and nematodes significantly differed between treatments when comparing the mudflat control and treatments of the high-shore (Table 5.11). *Macoma balthica* colonization of the mudflat control and treatments significantly differed during wks 4 and 6 (Appendix 2 Table 5.11) and the colonization of the mudflat control was higher than the treatments at wk 4 but decreased by 6 (Figure 5.9 a). *Hediste diversicolor* colonization of the mudflat control and treatments significantly differed between wks 4 to 6 and 8 to 10 and a gradual increase of treatment colonization occurred during the experiment, especially of treatment 2 and were greater than the mudflat control (Figure 5.9 c). Tellinacea j colonization was significantly higher in the mudflat control when compared to treatment 2 (Appendix 2 Table 5.11) and peak abundances of colonization of the mudflat control occurred at wks 2, 4 and 8. *Hediste diversicolor* j colonization of the treatment 2 was significantly higher than the mudflat control (Appendix 2 Table 5.11) (Figure 5.9 d).

The mean abundances of *T. benedii* and nematodes were significantly different in the mudflat control when compared to the treatments (Appendix 2 Table 5.11). *Tubificoides benedii* colonization was greater in the treatments when compared to the mudflat control on most sampling occasions (Figure 5.9 g) and nematodes colonization was higher in the treatments when compared to the mudflat control at wk 2 (Figure 5.9 h). Further repeated contrasts revealed significant interactions between time and treatment. However, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Table 5.11).

Table 5.10: Repeated measures ANOVA of abundance data for common taxa at the high-shore Control 1, Treatment 1 and Treatment 2, 2003.

Source	SS	DF	MS	F	P
(a) *M. balthica*					
Time	416	1	353	6.80	0.103
Treatment	**68**	**1**	**68**	**18.11**	**0.051**
Time x Treatment	257	1	201	2.41	0.244
(b) *Tellinacea* j					
Time	**384**	**2**	**231**	**25.94**	**0.010**
Treatment	24	2	12	1.75	0.285
Time x Treatment	38	2	24	0.41	0.652
(c) *H. diversicolor*					
Time	1532	1	1407	13.07	0.061
Treatment	163	1	162	3.30	0.211
Time x Treatment	402	1	278	1.64	0.317
(d) *H. diversicolor* j					
Time	**979**	**1**	**768**	**16.74**	**0.035**
Treatment	28	1	27	0.90	0.445
Time x Treatment	377	1	292	2.55	0.232
(e) *M. aestuarina*					
Time	7	1	6	1.50	0.344
Treatment	2	2	1	3.70	0.123
Time x Treatment	4	2	2	0.88	0.473
(f) *P. elegans*					
Time	50	2	29	2.71	0.193
Treatment	9	2	4	0.70	0.550
Time x Treatment	13	2	7	0.58	0.588
(g) *S. shrubsolii*					
Time	115	1	95	2.61	0.233
Treatment	27	2	13	1.60	0.309
Time x Treatment	173	1	154	1.73	0.315
(h) *T. benedii*					
Time	27894	2	16365	1.28	0.373
Treatment	555	2	277	0.31	0.752
Time x Treatment	38495	2	23588	0.92	0.461
(i) Nematoda					
Time	1372	2	867	8.39	0.056
Treatment	49	1	49	0.64	0.508
Time x Treatment	150	2	98	0.54	0.586

Bold values indicate significant differences, $p<0.05$. Refer to Figure 5.4 for control and treatment abbreviations.

Table 5.11: Repeated measures ANOVA of abundance data for common taxa at the high-shore Control 2, Treatment 1 and Treatment 2, 2003.

Source	SS	DF	MS	F	P
(a) *M. balthica*					
Time	**1186**	**2**	**621**	**5.61**	**0.046**
Treatment	794	1	794	3.59	0.199
Time x Treatment	1501	2	783	3.17	0.154
(b) *Tellinacea j*					
Time	1051	1	860	2.16	0.268
Treatment	**651**	**2**	**325**	**16.67**	**0.011**
Time x Treatment	557	1	474	0.74	0.492
(c) *H. diversicolor*					
Time	**912**	**1**	**636**	**23.69**	**0.017**
Treatment	514	1	503	10.17	0.084
Time x Treatment	423	2	236	2.40	0.217
(d) *H. diversicolor j*					
Time	404	1	347	7.48	0.095
Treatment	**175**	**2**	**87**	**17.08**	**0.011**
Time x Treatment	182	2	96	2.07	0.246
(e) *M. aestuarina*					
Time	11	2	6	0.76	0.524
Treatment	4	2	2	2.73	0.179
Time x Treatment	15	1	12	1.52	0.339
(f) *P. elegans*					
Time	115	1	80	3.43	0.170
Treatment	78	2	39	4.78	0.087
Time x Treatment	82	2	54	0.74	0.513
(g) *S. shrubsolii*					
Time	51	1	42	1.10	0.407
Treatment	41	2	20	1.39	0.348
Time x Treatment	176	1	170	1.96	0.295
(h) *T. benedii*					
Time	55881	2	30804	5.49	0.08
Treatment	**112638**	**2**	**56319**	**571.44**	**0.00**
Time x Treatment	66145	2	35177	1.22	0.39
(i) Nematoda					
Time	2086	2	1197	2.66	0.198
Treatment	**4571**	**1**	**4567**	**17.42**	**0.053**
Time x Treatment	6570	1	4954	3.94	0.157

Bold values indicate significant differences, $p<0.05$. Refer to Figure 5.4 for control and treatment abbreviations.

5.3.2.1.6 Similarity in community composition of the high-shore controls and treatments

The community structure in each treatment and control community at the high-shore were divided into three main groups, one formed by the mudflat controls for wks 2, 8 and 10 (Figure 5.10). The mudflat control from wk 4 was not linked to the first group and was defined by the highest mean abundance and number of species overall. In contrast, the mudflat control taken at wk 6 was most dissimilar to the remaining groups and was defined by a low mean abundance and species richness. The second group indicated a similarity of wk 4 treatments and mudflat control with wk 6 treatments, followed by wks 10 and 8 treatment 1, wk 8 treatment 2 and wk 10 defaunated control. The final group included the defaunated control from wks 2 to 8, wk 10 treatment 2 and wk 2 treatments.

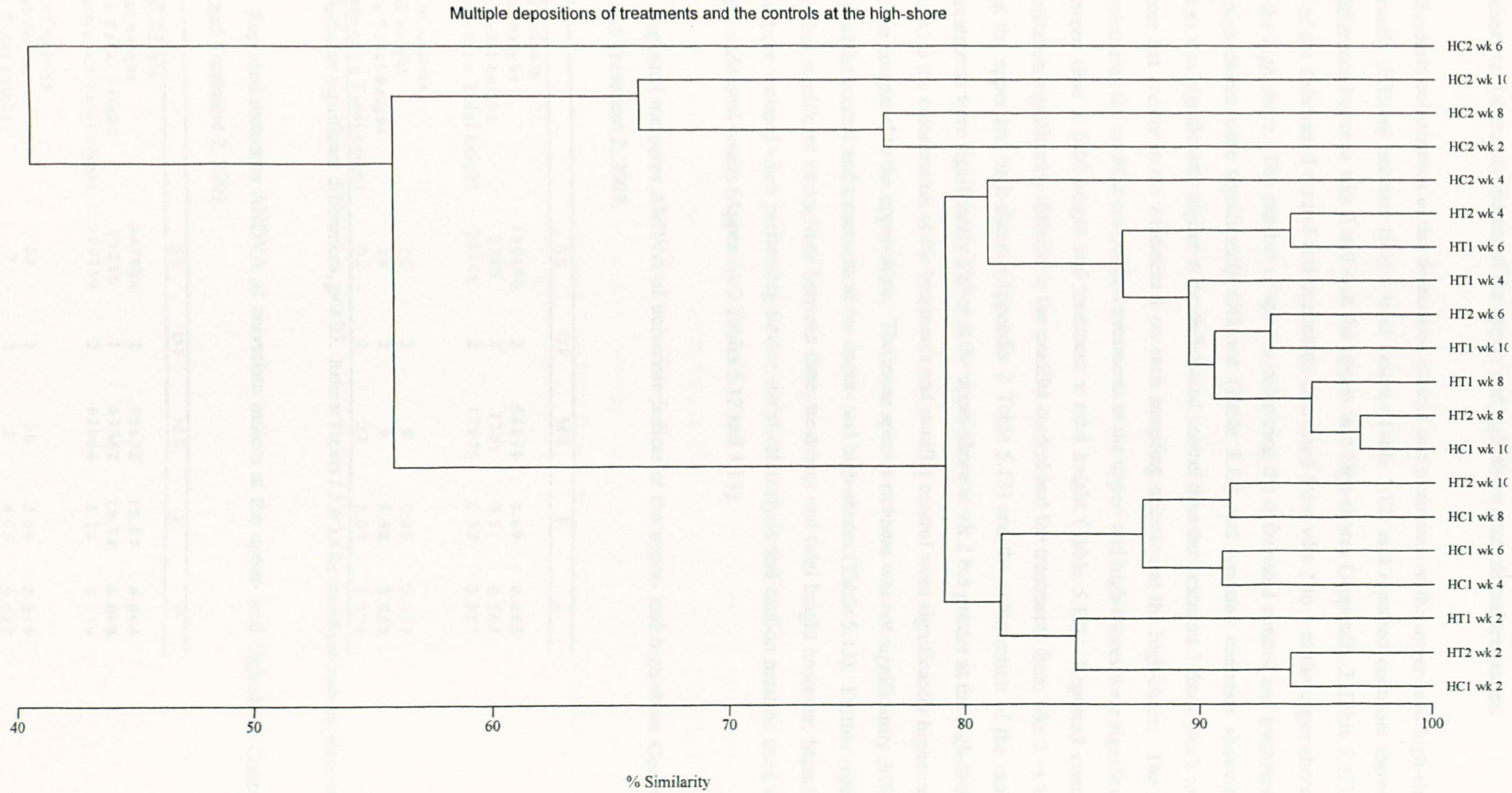


Figure 5.10: Assemblage composition similarity dendrogram of treatment type and sampling occasion at the high-shore.

5.3.2.1.7 Univariate community indices of the upper- and high-shore controls and treatments

The total individuals colonization of the defaunated control and treatments at the upper- and high-shores were significantly different between time x tidal height (Table 5.12) and repeated contrasts showed a significant difference between wks 2 and 4 at the upper- and high-shores (Appendix 2 Table 5.12), the colonization of the defaunated control and treatments decreased from wks 2 to 4 at the upper-shore but increased at the high-shore. The number of species colonizing the defaunated control and treatments at upper- and high-shores were significantly different (Table 5.12) and repeated contrasts showed the species richness was significantly higher in the defaunated control than the treatment 1 from wks 2 to 4 at the upper-shore but greater in the treatment 1 on each sampling occasion at the high-shore. The total individuals colonizing the mudflat control and treatments at the upper- and high-shores were significantly different between time x tidal height and treatment x tidal height (Table 5.13). Repeated contrasts showed colonization significantly differed in the mudflat control and the treatments from wks 2 to 4 and wks 4 to 6 at the upper and high-shores (Appendix 2 Table 5.13) and the colonization of the mudflat control and treatments were significantly higher at the upper-shore at wk 2 but greater at the high-shore at wks 4 and 6. Also the colonization of the treatments and mudflat control were significantly higher at the high-shore when compared to the upper-shore. The mean species richness was not significantly different between the mudflat control and treatments at the upper- and high-shores (Table 5.13). Further repeated contrasts revealed significant interactions between time, treatment and tidal height however, Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Tables 5.12 and 5.13).

Table 5.12: Repeated measures ANOVA of univariate indices at the upper- and high-shore Control 1, Treatment 1 and Treatment 2, 2003.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time x Tidal height	**116690**	**2**	**56616**	**4.69**	**0.043**
Treatment x Tidal height	2380	1	1709	0.51	0.561
Time x Treatment x Tidal height	26346	2	12975	0.57	0.587
(b) Number of species					
Time x Tidal height	16	2	9	1.80	0.232
Treatment x Tidal height	**14**	**2**	**9**	**6.58**	**0.033**
Time x Treatment x Tidal height	63	2	27	2.07	0.176

Bold values indicate significant differences, $p<0.05$. Refer to Figures 5.3 & 5.4 for control and treatment abbreviations.

Table 5.13: Repeated measures ANOVA of univariate indices at the upper- and high-shore Control 2, Treatment 1 and Treatment 2, 2003.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time x Tidal height	**147984**	**2**	**78632**	**12.37**	**0.004**
Treatment x Tidal height	**71216**	**1**	**63582**	**19.74**	**0.008**
Time x Treatment x Tidal height	110759	2	67004	1.24	0.339
(b) Number of species					
Time x Tidal height	55	1	50	2.09	0.218
Treatment x Tidal height	7	2	5	4.05	0.082
Time x Treatment x Tidal height	107	3	34	2.19	0.137

Bold values indicate significant differences, $p<0.05$. Refer to Figures 5.3 & 5.4 for control and treatment abbreviations.

5.3.2.1.8 Species abundances of the upper- and high-shore controls and treatments

Pygospio elegans colonization of the defaunated control and treatments at the upper- and high-shores significantly differed over time and significant differences of *H. diversicolor* colonization of treatment x tidal height were also observed (Table 5.14). Repeated contrasts revealed a significant difference of *P. elegans* colonization between wks 2 and 4 and a significant difference of *H. diversicolor* colonization of the defaunated control and treatment 1 at the upper- and high-shore areas (Appendix 2 Table 5.14). Few *H. diversicolor* individuals had colonized the defaunated control and treatments at wk 2 of the upper- and high-shore areas. However, colonization increased by wk 4 and was highest in the treatment 1 when compared to the defaunated control at the upper-shore and treatment 1 had fewer individuals than the defaunated control at the high-shore. Significant interactions of *H. diversicolor* j colonization between time x treatment x tidal height occurred when comparing wks 4 with 6 and wks 6 with 8 and colonization of the defaunated control and treatment 1 at the upper- and high-shore areas (Appendix 2 Table 5.14).

Macoma balthica, T. benedii, Enchytraeidae and nematodes colonization of the upper- and high-shore mudflat control and treatments significantly differed over time and significant differences of *H. diversicolor* and *H. diversicolor* j colonization between treatment x tidal height occurred (Table 5.15). Repeated contrasts revealed significant interactions when comparing the colonization of *T. benedii* and Enchytraeidae between wks 2 and 4, *M. balthica* colonization from wk 4 to 6 and nematode colonization from wk 6 to 8 and wk 8 to 10 at the upper- and high-shores (Appendix 2 Table 5.15). *Hediste diversicolor* j and *T. benedii* colonization were significantly different when comparing the mudflat control and treatment 1 at the upper- and high-shores and significant differences of *H. diversicolor* and *T. benedii* colonization of the mudflat control and treatment 2 (Appendix 2 Table 5.15). Further repeated contrasts revealed significant interactions between time, treatment and tidal height. However, in some cases Mauchly's test may have been violated when performing further statistical analysis and caution must be used when interpreting the additional results (Appendix 2 Tables 5.14 and 5.15).

Table 5.14: Repeated measures ANOVA of abundance data for common taxa at the upper- and high-shore Control 1, Treatment 1 and Treatment 2, 2003.

Source	SS	DF	MS	F	P
(a) *M. balthica*					
Time x Tidal height	**178**	**4**	**45**	**4.59**	**0.012**
Treatment x Tidal height	21	1	20	5.05	0.086
Time x Treatment x Tidal height	164	2	89	2.28	0.170
(b) *H. diversicolor*					
Time x Tidal height	201	4	50	1.57	0.231
Treatment x Tidal height	**254**	**2**	**127**	**6.80**	**0.019**
Time x Treatment x Tidal height	269	8	34	1.39	0.239
(c) *H. diversicolor* j					
Time x Tidal height	360	2	201	3.57	0.087
Treatment x Tidal height	27	2	14	0.87	0.456
Time x Treatment x Tidal height	**368**	**8**	**46**	**2.25**	**0.050**
(d) *M. aestuarina*					
Time x Tidal height	1072	1	872	4.32	0.091
Treatment x Tidal height	23	1	22	0.25	0.651
Time x Treatment x Tidal height	418	1	327	1.31	0.321
(e) *P. elegans*					
Time x Tidal height	**41**	**4**	**10**	**3.04**	**0.048**
Treatment x Tidal height	32	2	16	2.02	0.195
Time x Treatment x Tidal height	40	8	5	0.60	0.768
(f) *S. shrubsolii*					
Time x Tidal height	58	4	15	1.56	0.234
Treatment x Tidal height	49	2	24	3.58	0.077
Time x Treatment x Tidal height	110	8	14	1.00	0.453
(g) *T. benedii*					
Time x Tidal height	13860	4	3465	1.13	0.378
Treatment x Tidal height	28	2	14	0.01	0.986
Time x Treatment x Tidal height	16708	8	2089	0.72	0.669
(h) *Enchytraeidae*					
Time x Tidal height	82384	1	72640	5.60	0.068
Treatment x Tidal height	2274	1	2168	1.45	0.295
Time x Treatment x Tidal height	17732	2	9615	0.98	0.413
(i) Nematoda					
Time x Tidal height	67	4	17	0.31	0.867
Treatment x Tidal height	9	2	4	0.15	0.865
Time x Treatment x Tidal height	267	8	33	1.00	0.455

Bold values indicate significant differences, $p<0.05$. Refer to Figures 5.3 & 5.4 for control and treatment abbreviations.

Table 5.15: Repeated measures ANOVA of abundance data for common taxa at the upper- and high-shore Control 2, Treatment 1 and Treatment 2, 2003.

Source	SS	DF	MS	F	P
(a) *M. balthica*					
Time x Tidal height	**601**	**4**	**150**	**4.68**	**0.011**
Treatment x Tidal height	372	1	358	3.28	0.142
Time x Treatment x Tidal height	**787**	**8**	**98**	**2.98**	**0.013**
(b) *H. diversicolor*					
Time x Tidal height	176	1	134	2.76	0.155
Treatment x Tidal height	**424**	**2**	**212**	**6.12**	**0.024**
Time x Treatment x Tidal height	350	3	123	1.57	0.251
(c) *H. diversicolor* j					
Time x Tidal height	137	2	86	0.52	0.579
Treatment x Tidal height	**223**	**2**	**112**	**5.45**	**0.032**
Time x Treatment x Tidal height	575	2	328	2.26	0.176
(d) *M. aestuarina*					
Time x Tidal height	647	1	444	2.47	0.169
Treatment x Tidal height	182	1	176	2.09	0.221
Time x Treatment x Tidal height	493	1	349	1.29	0.326
(e) *P. elegans*					
Time x Tidal height	270	4	68	2.48	0.086
Treatment x Tidal height	99	2	50	2.46	0.147
Time x Treatment x Tidal height	**451**	**8**	**56**	**2.76**	**0.019**
(f) *S. shrubsolii*					
Time x Tidal height	130	4	33	1.45	0.264
Treatment x Tidal height	59	2	30	3.38	0.086
Time x Treatment x Tidal height	162	8	20	1.21	0.323
(g) *T. benedii*					
Time x Tidal height	**60510**	**4**	**15128**	**9.46**	**0.000**
Treatment x Tidal height	**75238**	**1**	**73466**	**34.35**	**0.004**
Time x Treatment x Tidal height	46902	2	22245	1.59	0.260
(h) *Enchytraeidae*					
Time x Tidal height	**52108**	**1**	**38737**	**8.72**	**0.025**
Treatment x Tidal height	253	2	127	0.16	0.852
Time x Treatment x Tidal height	40970	1	34682	1.78	0.250
(i) Nematoda					
Time x Tidal height	**1949**	**4**	**487**	**3.54**	**0.030**
Treatment x Tidal height	739	2	370	3.33	0.089
Time x Treatment x Tidal height	**4605**	**8**	**576**	**3.35**	**0.007**

Bold values indicate significant differences, $p<0.05$. Refer to Figures 5.3 & 5.4 for control and treatment abbreviations.

5.3.2.1.9 Similarity in community composition of the upper- and high-shore controls and treatments

The community structure of each treatment and control were arranged into two main groups, the first formed by most high-shore treatments and controls communities and the upper-shore mudflat control from wk 10 (Figure 5.11). The second group indicates the similarities between mostly the upper-shore treatments and controls communities with the addition of the high-shore mudflat controls of wks 6 and 10.

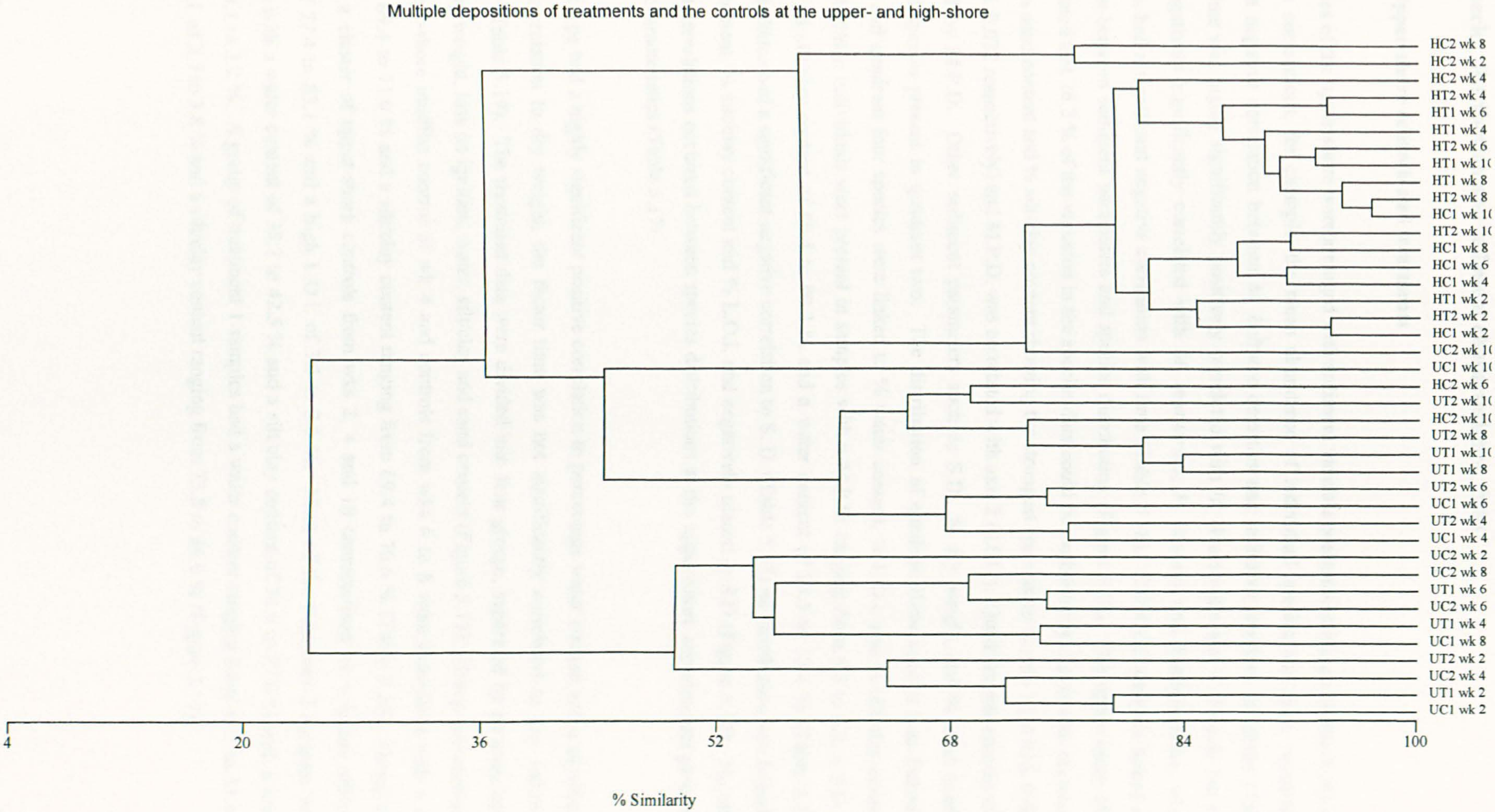


Figure 5.11: Assemblage composition similarity dendrogram of treatment type and sampling occasion at the upper- and high-shores, 2003.

5.3.3 Species distribution and sediment characteristics, 2003

5.3.3.1 Upper-shore controls and treatments

The species of the upper-shore were arranged with sediment variable preferences ranges (Table 5.16) and Spearman correlations, for example, the mean abundance of individual species and time, revealed a significant negative correlation between *M. balthica* densities and inclusive standard deviation (Table 5.17). Time was highly significantly positively correlated with *H. diversicolor* and *T. benedii* but was highly negatively significantly correlated with *M. aestuarina*, *P. litoralis* and Enchytraeidae, whilst nematodes had a significant negative correlation with time (Table 5.18). CANOCO analysis linked any correlation between sediment parameters and species distribution (Figure 5.12). The upper-shore 2003 data indicated that 26.2 % of the variation in the species data could be explained by 2 axis with skewness, M.P.D., % sand content and % silt/clay content showing the strongest correlation to axis 1 (-0.016, 0.020, 0.022 and -0.022 respectively) and M.P.D. was correlated with axis 2 (0.033). Quadrant one species were influenced by M.P.D. Other sediment parameters such as S.D., % dry weight and % sand content influenced species present in quadrant two. The distribution of quadrant three species was linked to skewness and quadrant four species were linked to % water content, % L.O.I. and % silt/clay content. *Macoma balthica* individuals were present in samples with a M.P.D. ranging from 5.3 to 6.2, a S.D. of 1.8 to 2.1, a silt/clay content of 69.4 to 90.2 % and a water content of 29.5 to 53.4 % (Table 5.16). *Macoma balthica* had a significant negative correlation to S. D. (Table 5.17) its distribution was linked to % water content, % silt/clay content and % L.O.I. and negatively placed to S.D (Figure 5.12). No other significant correlations occurred between species distributions at the upper-shore experimental plots and sediment characteristics (Table 5.17).

Treatment type had a highly significant positive correlation to percentage water content and a significant negative correlation to dry weight, the factor time was not significantly correlated to any sediment parameter (Table 5.19). The treatment data were divided into four groups, separated by an association towards dry weight, loss on ignition, water, silt/clay and sand content (Figure 5.13). Group one consisted of the upper-shore mudflat control of wk 4 and controls from wks 6 to 8 were associated with a dry weight of 69.4 to 71.0 % and a silt/clay content ranging from 69.4 to 70.6 % (Table 5.20). Group two contained a cluster of upper-shore controls from wks 2, 4 and 10 characterised by a higher silt/clay content of 77.4 to 83.1 % and a high L.O.I. of 3.3 to 3.6 %. Most of the treatment 2 samples were associated with a water content of 38.7 to 42.5 % and a silt/clay content of 74.0 to 77.0 % with a lower L.O.I. of 3.1 to 3.2 %. A group of treatment 1 samples had a water content ranging from 45.7 to 53.4 % and a L.O.I. of 2.7 to 3.8 % and a silt/clay content ranging from 73.8 to 86.9 % (Figure 5.13).

Table 5.16: Arrangement of upper-shore species according to sediment preferences.

Species	Ranges							
	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content
M. balthica	5.34 - 6.15	1.79 - 2.06	0.05 - 0.51	9.79 - 30.62	69.38 - 90.21	46.07 - 70.98	2.66 - 3.82	29.46 - 53.43
Tellinacea j	5.34 - 6.15	1.79 - 2.06	0.05 - 0.51	9.79 - 30.62	69.38 - 90.21	46.07 - 70.98	2.66 - 3.82	29.46 - 53.43
H. ulvae	5.34 - 6.15	1.79 - 2.06	0.05 - 0.51	9.79 - 30.62	69.38 - 90.21	46.07 - 70.98	2.66 - 3.82	29.46 - 53.43
H. diversicolor	5.34 - 6.15	1.79 - 2.06	0.05 - 0.51	9.79 - 30.62	69.38 - 90.21	46.07 - 70.98	2.66 - 3.82	29.46 - 53.43
H. diversicolor j	5.34 - 6.15	1.79 - 2.06	0.05 - 0.51	9.79 - 30.62	69.38 - 90.21	46.07 - 70.98	2.68 - 3.82	30.06 - 53.43
M. aestuarina	5.34 - 6.15	1.79 - 2.06	0.05 - 0.51	9.79 - 30.62	69.38 - 90.21	46.07 - 70.98	2.66 - 3.82	29.46 - 53.43
P. elegans	5.34 - 6.15	1.79 - 2.06	0.05 - 0.51	9.79 - 30.62	69.38 - 90.21	46.07 - 70.98	2.66 - 3.82	29.46 - 53.43
S. shrubsolii	5.34 - 6.15	1.79 - 2.06	0.05 - 0.51	9.79 - 30.62	69.38 - 90.21	46.57 - 70.98	2.66 - 3.82	29.46 - 53.43
T. benedii	5.34 - 6.15	1.79 - 2.06	0.05 - 0.51	9.79 - 30.62	69.38 - 90.21	46.07 - 70.98	2.66 - 3.82	29.46 - 53.43
P. litoralis	5.35 - 6.09	1.79 - 2.06	0.15 - 0.51	9.79 - 30.15	69.64 - 90.21	52.21 - 70.98	2.66 - 3.57	29.46 - 47.79
Enchytraeidae	5.34 - 6.15	1.79 - 2.06	0.05 - 0.51	9.79 - 30.62	69.38 - 90.21	46.07 - 70.98	2.66 - 3.82	29.46 - 53.43
Nematoda	5.34 - 6.15	1.79 - 2.06	0.05 - 0.51	9.79 - 30.62	69.38 - 90.21	46.07 - 70.98	2.66 - 3.82	29.46 - 53.43

Table 5.17: Significant correlations between upper-shore mean abundances of individual species and sediment characteristics, using Spearman correlation coefficient.

Species	Sediment characteristics							
	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content
M. balthica	ns	-	ns	ns	ns	ns	ns	ns
Tellinacea j	ns	ns	ns	ns	ns	ns	ns	ns
H. ulvae	ns	ns	ns	ns	ns	ns	ns	ns
H. diversicolor	ns	ns	ns	ns	ns	ns	ns	ns
H. diversicolor j	ns	ns	ns	ns	ns	ns	ns	ns
M. aestuarina	ns	ns	ns	ns	ns	ns	ns	ns
P. elegans	ns	ns	ns	ns	ns	ns	ns	ns
S. shrubsolii	ns	ns	ns	ns	ns	ns	ns	ns
T. benedii	ns	ns	ns	ns	ns	ns	ns	ns
P. litoralis	ns	ns	ns	ns	ns	ns	ns	ns
Enchytraeidae	ns	ns	ns	ns	ns	ns	ns	ns
Nematoda	ns	ns	ns	ns	ns	ns	ns	ns

Key

p - values		Significance
p> 0.05	ns	not significant
0.01<p<0.05	- or +	Significant negative or positive correlation
0.001<p<0.01	- - or + +	very significant negative or positive correlation

Table 5.18: Significant correlations between upper-shore mean abundance of individual species and time, using Spearman correlation coefficient.

Species	Species, treatment and time												
	M. balthica	Tellinacea j	*H. ulvae*	*H. diversicolor*	*H. diversicolor* j	*M. aestuarina*	*P. elegans*	*S. shrubsolii*	*T. benedii*	*P. litoralis*	Enchytraeidae	Nematoda	Week
M. balthica		ns	ns	ns	ns	ns	ns	++	++	ns	ns	ns	ns
Tellinacea j	ns		ns	ns	ns	ns	+	ns	ns	ns	ns	ns	ns
H. ulvae	ns	ns		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
H. diversicolor	ns	ns	ns		ns	--	ns	ns	++	--	--	ns	++
H. diversicolor j	ns	ns	ns	ns		ns	ns	ns	ns	ns	ns	ns	ns
M. aestuarina	ns	ns	ns	--	ns		ns	ns	ns	++	ns	+	--
P. elegans	ns	+	ns	ns	ns	ns		++	ns	ns	ns	+	ns
S. shrubsolii	++	ns	ns	ns	ns	ns	++		ns	ns	ns	++	ns
T. benedii	++	ns	ns	++	ns	ns	ns	ns		ns	--	ns	++
P. litoralis	ns	ns	ns	--	ns	++	ns	ns	ns		++	+	--
Enchytraeidae	ns	ns	ns	--	ns	ns	ns	ns	--	++		+	--
Nematoda	ns	ns	ns	ns	ns	+	+	++	ns	+	+		-

Key

p - values		Significance
p> 0.05	ns	not significant
0.01<p<0.05	- or +	Significant negative or positive correlation
0.001<p<0.01	- - or + +	very significant negative or positive correlation

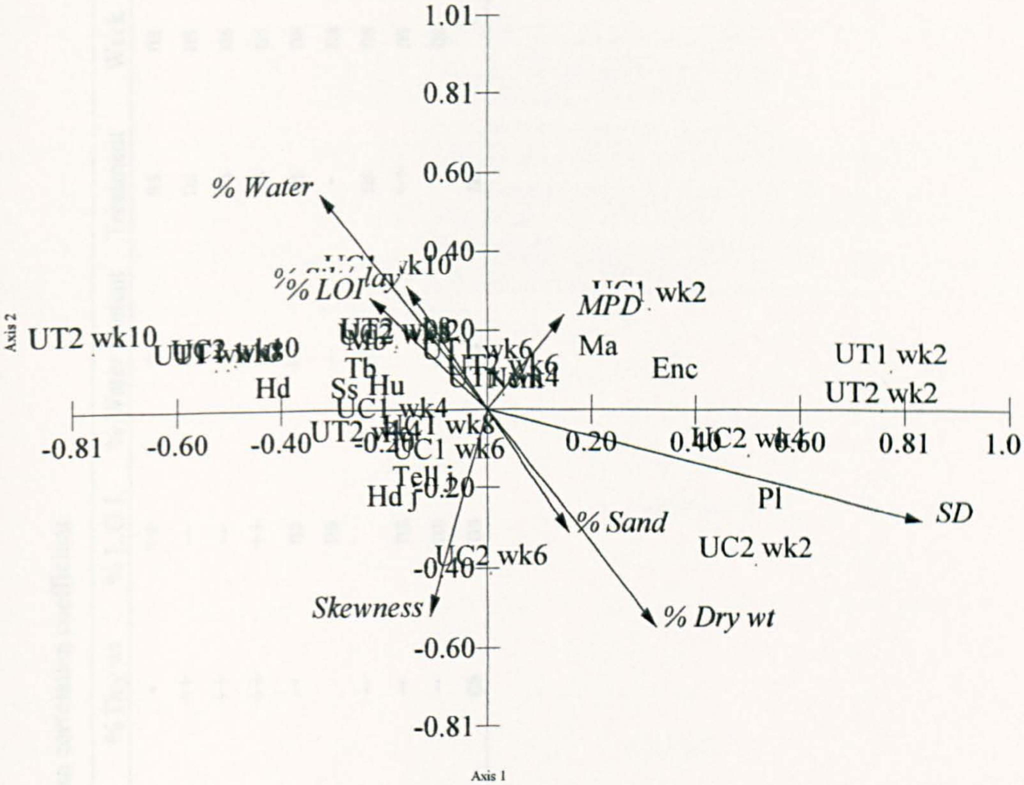


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Figure 5.12: CCA of upper-shore species distribution in relation to sediment characteristics on square-root transformed data.

Species key:

M. balthica (Mb)	*H. diversicolor* (Hd)	*P. elegans* (Pe)	*P. litoralis* (Pl)
Tellinacea j (Tell j)	*H. diversicolor* j (Hdj)	*S. shrubsolii* (Ss)	Enchytraeidae (Enc)
H. ulvae (Hu)	*M. aestuarina* (Ma)	*T. benedii* (Tb)	Nematoda (Nem)

Table 5.19: Significant correlations between upper-shore sediment characteristics, using Spearman correlation coefficient.

Sediment variables	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content	Treatment	Week
Inc. M.P.D. Ø		--	--	--	++	-	++	+	ns	ns
Inc. S.D. Ø	--		++	++	--	++	--	--	ns	ns
Inc. Skewness	--	++		++	--	++	--	--	ns	ns
% Sand content	--	++	++		--	++	++	--	ns	ns
% Silt/clay content	++	--	--	--		--	ns	++	ns	ns
% Dry wt	-	++	++	++	--		ns	--	-	ns
% L.O.I.	++	ns	--	--	++	--		ns	ns	ns
% Water content	+	--	--	--	++	--	ns		++	ns
Treatment	ns	ns	ns	ns	ns	--	ns	++		ns
Week	ns	ns	ns	ns	ns	ns	ns	ns	ns	

Key

p - values		Significance
p> 0.05	ns	not significant
0.01<p<0.05	- or +	Significant negative or positive correlation
0.001<p<0.01	- - or + +	very significant negative or positive correlation

Table 5.20: Analysis of upper-shore groups sorted by PCA according to sediment characteristics.

Group	Site	Features
1	UC1wk 6 UC1 wk 8 UC2 wk 4 UC2 wk 6 UC2 wk 8	Dry wt % between 69.35 & 70.98% Silt/clay % between 69.38 & 70.55%
2	UC1 wk 2 UC1 wk 4 UC1 wk 10 UC2 wk 2 UC2 wk 10	LOI % between 3.33 & 3.57% Silt/clay % between 77.41 & 83.05%
3	UT2 wk 2 UT2 wk 6 UT2 wk 8 UT2 wk 10	LOI % between 3.09 & 3.19%. Silt/clay % between 73.99 & 77.02%. Water content of between 38.66 & 42.51%
4	UT1 wk 2 UT1 wk 4 UT1 wk 6 UT1 wk 8 UT1 wk 10	LOI % between 2.71 & 3.82%. Silt/clay % between 73.84 & 86.93%. Water content of between 45.68 & 53.43%
Outlier	UT2 wk 4	Silt/clay content of 90.21%

Refer to Figure 5.3 for control and treatment abbreviations.

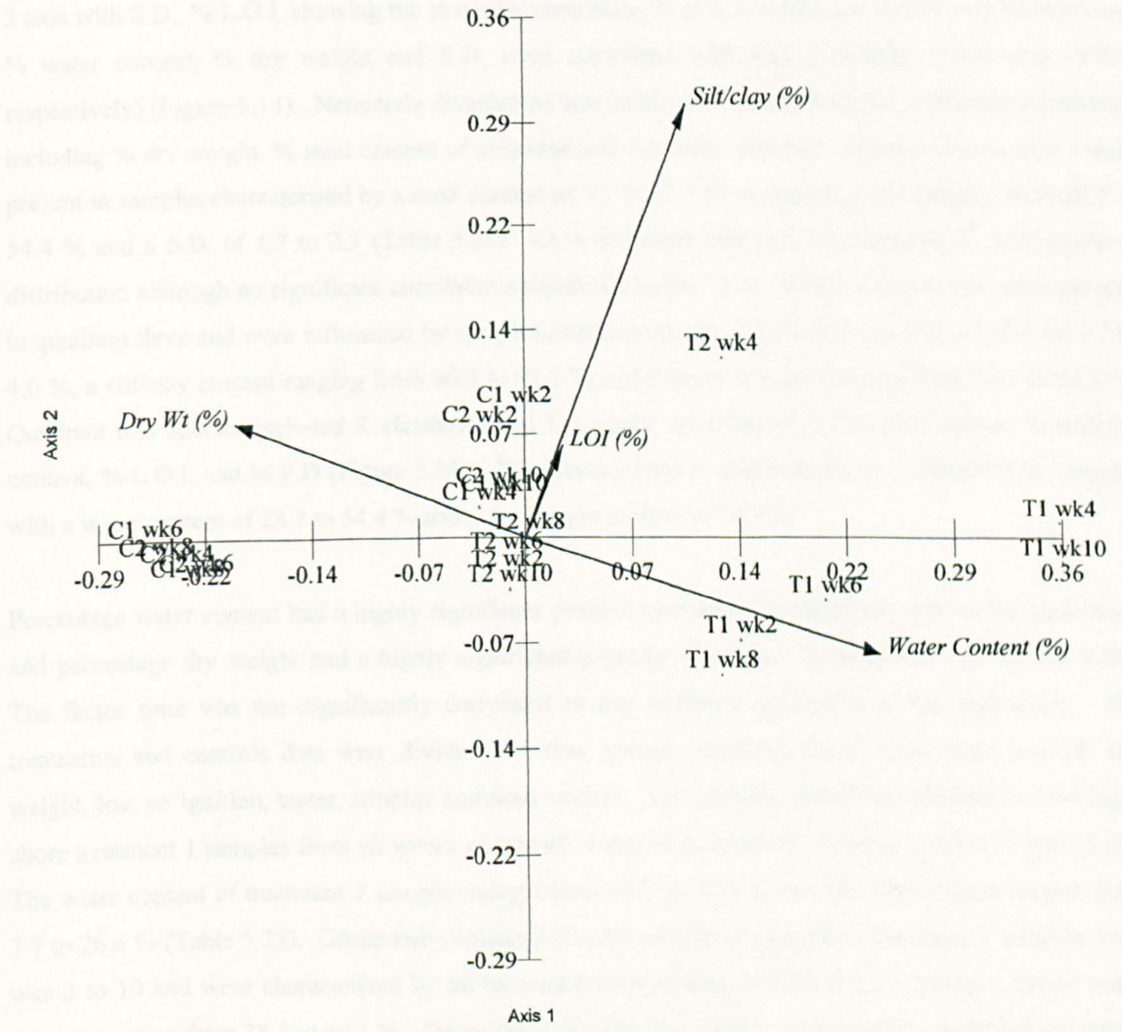

Figure 5.13: PCA of the sediment characteristics of all upper-shore treatments and controls on square-root transformed data. Refer to Figure 5.3 for control and treatment abbreviations.

5.3.3.2 High-shore controls and treatments

The species of the high-shore were arranged with sediment variables preferences ranges (Table 5.21) and Spearman correlations, for example, the mean abundance of individual species and time revealed *T. benedii* had a significant positive correlation to % water content and a significant negative correlation to % dry weight (Table 5.22). *Hediste diversicolor* had a highly significant positive correlation to time and *M. balthica*, Tellinacea j and nematode densities had a highly significant negative correlation to time, also *P. elegans* and *S. shrubsolii* had a significant negative correlation to time (Table 5.23). CANOCO analysis linked any correlation between sediment parameters and species distributions at the high-shore 2003. The high-shore data indicated that 11.6 % of the variation in the species data could be explained by 2 axis with S.D., % L.O.I. showing the strongest correlation to axis 1 (0.020 and -0.045 respectively) and % water content, % dry weight and S.D. were correlated with axis 2 (0.030, -0.030 and –0.030 respectively) (Figure 5.14). Nematoda distribution was influenced by quadrant two sediment parameters including % dry weight, % sand content of sediment and skewness and S.D. *Hediste diversicolor* j were present in samples characterised by a sand content of 7.7 to 33.1 %, a water content ranging from 28.7 to 54.4 % and a S.D. of 1.7 to 2.3 (Table 5.21). CCA indicated that axis 1 influenced *H. diversicolor* j distribution although no significant correlations occurred (Table 5.22). *Hediste diversicolor* were present in quadrant three and were influenced by samples characterised by a S.D. of 1.7 to 2.3, a L.O.I. of 2.7 to 4.0 %, a silt/clay content ranging from 66.9 to 92.3 % and a water content ranging from 28.7 to 54.4 %. Quadrant four species included *S. shrubsolii* and *T. benedii*, were linked to % water content, % silt/clay content, % L.O.I. and M.P.D (Figure 5.14). *Tubificoides benedii* distribution was influenced by samples with a water content of 28.7 to 54.4 % and a dry weight of 45.6 to 71.3 %.

Percentage water content had a highly significant positive correlation to treatment type at the high-shore and percentage dry weight had a highly significant negative correlation to treatment type (Table 5.24). The factor time was not significantly correlated to any sediment parameter at the high-shore. The treatments and controls data were divided into four groups, separated by an association towards dry weight, loss on ignition, water, silt/clay and sand content. For example, group one consisted of the high-shore treatment 1 samples from all weeks except wk 4 and were linked to % water content (Figure 5.15). The water content of treatment 1 samples ranged from 44.7 to 54.4 % and the sand content ranged from 7.7 to 26.6 % (Table 5.25). Group two contained a wider cluster of high-shore treatment 2 samples from wks 2 to 10 and were characterised by an increased sand content of 22.0 to 33.1 % and a lower water content ranging from 38.5 to 40.1 %. Group three, the smallest cluster, contained the controls from wks 2 and 10 were associated with a silt/clay content of 77.8 to 80.5 % and a L.O.I. of 3.4 to 3.6 % and the fourth group consisted of controls from wks 4 to 8 were categorized by a dry weight of 62.8 to 71.3 % and a sand content of 23.5 to 33.0 %.

Table 5.21: Arrangement of high-shore species according to sediment preferences.

Species	Ranges							
	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content
M. balthica	4.89-6.24	1.68-2.27	0.00-0.50	7.71-33.14	66.86-92.29	45.56-71.28	2.68-3.95	28.72-54.44
Tellinacea j	4.89-6.24	1.68-2.27	0.00-0.50	7.71-33.14	66.86-92.29	45.56-70.66	2.73-3.95	29.34-54.44
H. diversicolor	4.89-6.24	1.68-2.27	0.00-0.50	7.71-33.14	66.86-92.29	45.56-71.28	2.68-3.95	28.72-54.44
H. diversicolor j	4.89-6.24	1.68-2.27	0.00-0.50	7.71-33.14	66.86-92.29	45.56-71.28	2.68-3.95	28.72-54.44
P. elegans	4.89-6.24	1.68-2.27	0.00-0.50	7.71-33.14	66.86-92.29	45.56-71.28	2.73-3.95	29.34-54.44
S. shrubsolii	4.89-6.24	1.68-2.27	0.00-0.50	7.71-33.14	66.86-92.29	45.56-71.28	2.68-3.95	28.72-54.44
T. benedii	4.89-6.24	1.68-2.27	0.00-0.50	7.71-33.14	66.86-92.29	45.56-71.28	2.68-3.95	28.72-54.44
Nematoda	4.89-6.24	1.68-2.27	0.00-0.50	7.71-33.14	66.86-92.29	45.56-71.28	2.68-3.95	28.72-54.44

Table 5.22: Significant correlations between high-shore mean abundances of individual species and sediment characteristics, using Spearman correlation coefficient.

Species	Sediment characteristics							
	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content
M. balthica	ns	ns	ns	ns	ns	ns	ns	ns
Tellinacea j	ns	ns	ns	ns	ns	ns	ns	ns
H. diversicolor	ns	ns	ns	ns	ns	ns	ns	ns
H. diversicolor j	ns	ns	ns	ns	ns	ns	ns	ns
P. elegans	ns	ns	ns	ns	ns	ns	ns	ns
S. shrubsolii	ns	ns	ns	ns	ns	ns	ns	ns
T. benedii	ns	ns	ns	ns	ns	-	ns	+
Nematoda	ns	ns	ns	ns	ns	ns	ns	ns

Key

p - values		Significance
p> 0.05	ns	not significant
0.01<p<0.05	- or +	Significant negative or positive correlation
0.001<p<0.01	- - or + +	very significant negative or positive correlation

Table 5.23: Significant correlations between high-shore mean abundance of individual species and time, using Spearman correlation coefficient.

Species	Species, treatment and time								
	M. balthica	Tellinacea j	*H. diversicolor*	*Nereidae* j	*P. elegans*	*S. shrubsolii*	*T. benedii*	Nematoda	Week
M. balthica		++	--	ns	++	+	ns	++	--
Tellinacea j	++		--	ns	++	+	ns	++	--
H. diversicolor	--	--		+	--	ns	ns	--	++
H. diversicolor j	ns	ns	+		-	ns	+	ns	ns
P. elegans	++	++	--	-		ns	ns	++	-
S. shrubsolii	+	+	ns	ns	ns		+	ns	-
T. benedii	ns	ns	ns	+	ns	+		ns	ns
Nematoda	++	++	--	ns	++	ns	ns		--

Key

p - values		Significance
$p > 0.05$	ns	not significant
$0.01 < p < 0.05$	- or +	Significant negative or positive correlation
$0.001 < p < 0.01$	- - or + +	very significant negative or positive correlation

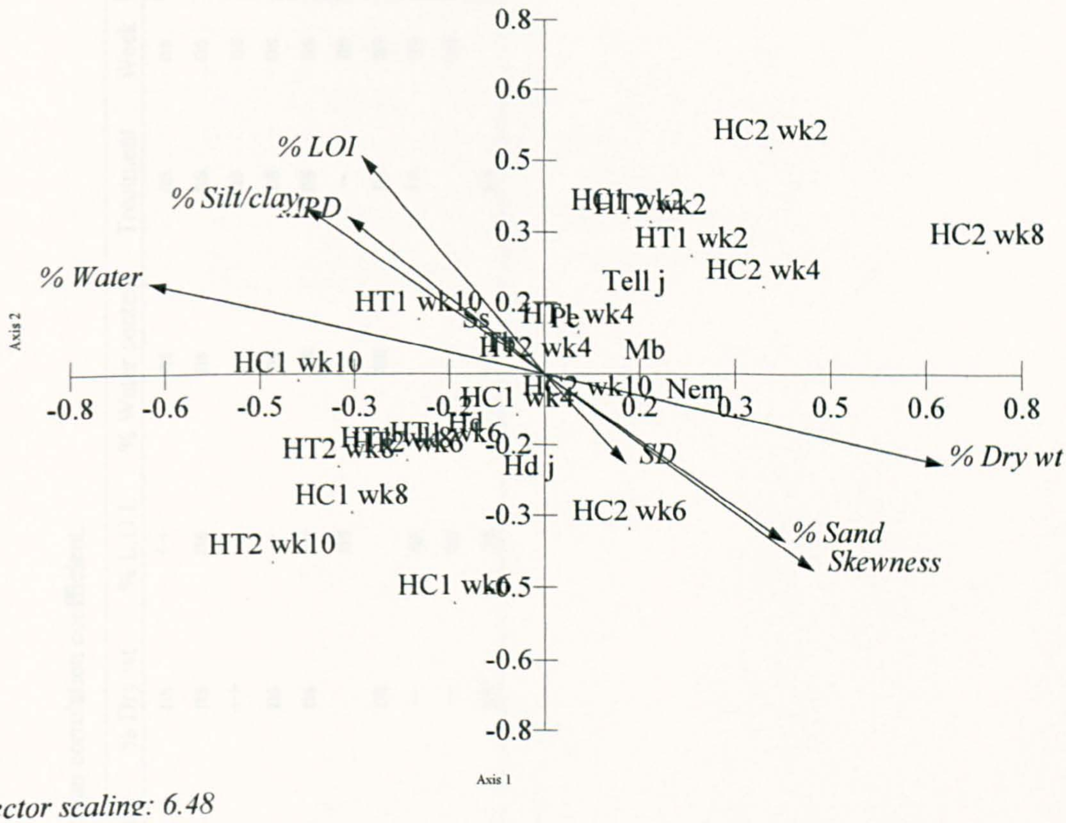

Figure 5.14: CCA of high-shore species distribution in relation to sediment characteristics on square-root transformed data.

Species key:

M. balthica (Mb)	Tellinacea j (Tell j)	*H. diversicolor* (Hd)	*H. diversicolor* j (Hdj)
P. elegans (Pe)	*S. shrubsolii* (Ss)	*T. benedii* (Tb)	Nematoda (Nem)

Table 5.24: Significant correlations between high-shore sediment characteristics, using Spearman correlation coefficient.

Sediment variables	Inc. M.P.D. Ø	Inc. S.D. Ø	Inc. Skewness	% Sand content	% Silt/clay	% Dry wt	% L.O.I.	% Water content	Treatment	Week
Inc. M.P.D. Ø		ns	--	--	++	ns	++	ns	ns	ns
Inc. S.D. Ø	ns		ns	+	-	ns	ns	ns	ns	ns
Inc. Skewness	--	ns		++	--	++	--	--	ns	ns
% Sand content	--	+	++		--	ns	--	ns	ns	ns
% Silt/clay content	++	-	--	--		ns	++	ns	ns	ns
% Dry wt	ns	ns	++	ns	ns		ns	--	--	ns
% L.O.I.	++	ns	--	--	++	ns		ns	ns	ns
% Water content	ns	ns	--	ns	ns	--	ns		++	ns
Treatment	ns	ns	ns	ns	ns	--	ns	++		ns
Week	ns	ns	ns	ns	ns	ns	ns	ns	ns	

Key

p - values		Significance
p> 0.05	ns	not significant
0.01<p<0.05	- or +	Significant negative or positive correlation
0.001<p<0.01	- - or + +	very significant negative or positive correlation

Table 5.25: Analysis of high-shore groups sorted by PCA according to sediment characteristics.

Group	Site	Features
1	HT1 wk 2 HT1 wk 4 HT1 wk 6 HT1 wk 8 HT1 wk 10	Water content between 44.65 & 54.44% Sand content between 7.71 & 26.58%
2	HT2 wk 2 HT2 wk 4 HT2 wk 6 HT2 wk 8 HT2 wk 10	Water content between 38.50 & 40.12% Sand content between 21.98 & 33.14%
3	HC1 wk 2 HC1 wk10 HC2 wk 2 HC2 wk 10	LOI % between 3.38 & 3.59% Silt/clay % between 77.75 & 80.46%. Water content between 36.80 & 37.92 %
4	HC1 wk 4 HC1 wk 6 HC1 wk 8 HC2 wk 4 HC2 wk 6 HC2 wk 8	Sand content between 23.47 & 32.99% Dry wt % between 62.75 & 71.28%

Refer to Figure 5.4 for control and treatment abbreviations.

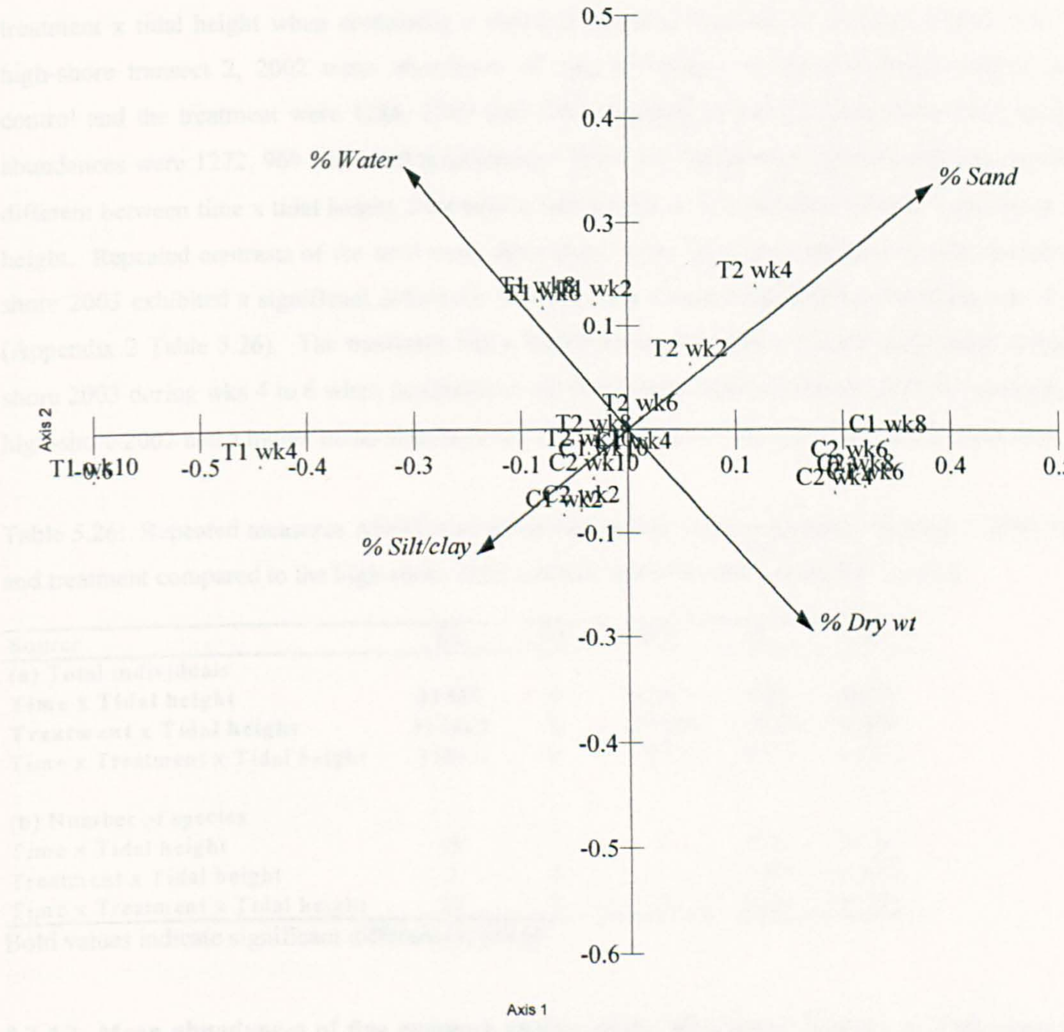

Figure 5.15: PCA of the sediment characteristics of all high-shore treatments and controls on square-root transformed data. Refer to Figure 5.4 for control and treatment abbreviations.

5.3.4 Temporal variation of species colonization and tidal height comparisons of 2002 and 2003

5.3.4.1 Univariate community indices of the high-shore transect 2, 2002 compared to the high-shore 2003, weeks two to ten

The mean abundance of total individuals were compared between the high-shore transect 2, 2002 treatment and controls with the high-shore 2003 treatment 2 and controls during wks 2 to 10 to compare temporal differences at the high-shore tidal height (Table 5.26), the sampling occasions were the same dates for each year. The total individuals were significantly different between time x tidal height and treatment x tidal height when comparing a repeated measures analysis of variance (Table 5.26). The high-shore transect 2, 2002 mean abundance of total individuals in the defaunated control, mudflat control and the treatment were 1288, 2509 and 1262 respectively and the high-shore 2003 total mean abundances were 1272, 969 and 1320 respectively. However, the species richness was not significantly different between time x tidal height, treatment x tidal height or an interaction of time x treatment x tidal height. Repeated contrasts of the total mean abundance at the high-shore transect 2, 2002 and the high-shore 2003 exhibited a significant difference between time x tidal height when comparing wks 4 with 6 (Appendix 2 Table 5.26). The treatment had a higher mean abundance of total individuals at the high-shore 2003 during wks 4 to 6 when compared to the defaunated control however, both the controls of the high-shore 2002 had a higher mean abundance of total individuals when compared to the treatment.

Table 5.26: Repeated measures ANOVA of univariate indices at the high-shore transect 2, 2002 controls and treatment compared to the high-shore 2003 controls and treatment 2 from wks 2 to 10.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time x Tidal height	**81869**	**4**	**20467**	**3.33**	**0.036**
Treatment x Tidal height	**214418**	**2**	**107209**	**125.68**	**0.000**
Time x Treatment x Tidal height	31017	8	3877	0.67	0.714
(b) Number of species					
Time x Tidal height	11	1	7	0.94	0.411
Treatment x Tidal height	2	2	1	0.89	0.448
Time x Treatment x Tidal height	33	2	15	1.06	0.394

Bold values indicate significant differences, $p<0.05$.

5.3.4.2 Mean abundances of five common species of the high-shore transect 2, 2002 compared to the high-shore 2003 wks 2 to 10

Mean abundance of species in the controls and treatment of the high-shore transect 2, 2002 were compared to the high-shore 2003 by a repeated measures analysis of variance (Table 5.27). Significant time x tidal height interactions occurred when comparing *T. benedii* mean abundance in the controls and treatment of the high-shores between 2002 and 2003 also, *T. benedii* and *M. balthica* mean abundances significantly differed between treatment x tidal height (Table 5.27). Repeated contrasts revealed a significant difference between time x tidal height of *T. benedii* mean abundance during wks 4 to 6 at the high-shores during 2002 and 2003 (Appendix 2 Table 5.27) and the mean abundance was higher in treatment 2 of 2003 at wks 4 and 6 when compared to the controls. The treatment mean abundance was equal to the defaunated control during 2002 but less than the mudflat control between wks 4 and 6. Other, repeated contrasts revealed a significant difference between treatment x tidal height when comparing the mean abundances of *M. balthica* and *T. benedii* in the mudflat control compared with the treatment at the high-shores of 2002 and 2003. The high-shore transect 2, 2002 mean abundance of *M. balthica* was greater in the mudflat control (170) than the treatment (22) from wks 2 to 10 similarly, the mean abundance in 2003 was greater in the mudflat control (80) than treatment 2 (32) and the mudflat control of 2002 was higher than 2003. *Tubificoides benedii* mean abundance was higher in the treatment (1111) than the mudflat control (592) of the high-shore 2003 when compared to 2002 treatment (696) and mudflat control (932).

Table 5.27: Repeated measures ANOVA of five common species at the high-shore transect 2, 2002 controls and treatment compared to the high-shore 2003 controls and treatment 2 from wks 2 to 10.

Source	SS	DF	MS	F	P
M. balthica					
Time x Tidal height	291	4	73	1.27	0.323
Treatment x Tidal height	**1700**	**2**	**850**	**13.21**	**0.003**
Time x Treatment x Tidal height	891	8	111	1.72	0.131
H. diversicolor j					
Time x Tidal height	64	4	16	0.57	0.688
Treatment x Tidal height	73	2	36	3.15	0.098
Time x Treatment x Tidal height	**408**	**8**	**51**	**2.69**	**0.022**
P. elegans					
Time x Tidal height	74	4	18	2.36	0.097
Treatment x Tidal height	21	2	11	1.33	0.317
Time x Treatment x Tidal height	144	8	18	2.13	0.062
T. benedii					
Time x Tidal height	**83953**	**4**	**20988**	**4.63**	**0.011**
Treatment x Tidal height	**114662**	**2**	**57331**	**31.16**	**0.000**
Time x Treatment x Tidal height	29516	8	3690	1.13	0.370
Nematoda					
Time x Tidal height	1205	1	812	0.56	0.551
Treatment x Tidal height	1040	2	520	1.57	0.266
Time x Treatment x Tidal height	6427	2	3341	1.59	0.264

Bold values indicate significant differences, $p < 0.05$.

5.3.4.3 Univariate community indices of the high- and mid-shore transect 2, 2002 compared to the upper- and high-shore 2003 wks 2 to 10

The mean abundance of total individuals were compared between the high- and mid-shore treatment and controls 2002 with the upper- and high-shore treatment 2 and controls 2003 during wks 2 to 10, as sampling occasions were the same dates for each year (Table 5.28). The total individuals were significantly different between time x tidal height and treatment x tidal height (Table 5.28). The species richness was significantly different between treatment x tidal height and time x treatment x tidal height. The high-shore 2002 controls and treatment had the greatest abundance of total individuals (15173), followed by the high-shore 2003 controls and treatments (14402), the mid-shore 2002 (7190) and upper-shore 2003 (8295) were less.

Repeated contrasts of the total individuals at the high- and mid-shores 2002 and the upper- and high-shores 2003 exhibited a significant difference between time x tidal height when comparing wks 4 with 6 and wks 6 with 8 also, the species richness significantly differed during wks 4 and 6 (Appendix 2 Table 5.28). The total individuals were greatest in the mudflat control at each tidal height during wks 4 to 6 (except at the high-shore 2003 wk 6 when the treatment had the highest mean abundance). The total individuals and species richness significantly differed between repeated contrasts of treatment x tidal heights of 2002 and 2003 in particular the mudflat control differed to the treatment. Also the species richness significantly differed during wks 4 to 6 when comparing the mudflat control with the treatment and between tidal heights of 2002 and 2003. The species richness in the treatment at the upper-shore wk 4 and the high-shore wk 6 2003 were greater than the mudflat control and the mudflat control had the highest species richness at all other tidal heights during wks 4 and 6. Repeated contrasts of the number of species significantly differed between time x treatment x tidal height, during wks 6 and 8 when comparing the mudflat control and treatment of the high- and mid-shores 2002 with the upper- and high-shores 2003. The species richness in the treatment at the high-shore wk 6 2003 was higher than the mudflat control and the mudflat control had the greatest species richness at remaining tidal heights during wks 6 and 8.

Table 5.28: Repeated measures ANOVA of univariate indices at the high- and mid-shores transect 2, 2002 controls and treatment 1 compared with the upper- and high-shores 2003 controls and treatment 2 from wks 2 to 10.

Source	SS	DF	MS	F	P
(a) Total individuals					
Time x Tidal height	**306536**	**12**	**25545**	**3.75**	**0.001**
Treatment x Tidal height	**269293**	**6**	**44882**	**22.39**	**0.000**
Time x Treatment x Tidal height	205226	24	8551	1.25	0.234
(b) Number of species					
Time x Tidal height	108	6	19	1.88	0.151
Treatment x Tidal height	**112**	**6**	**19**	**18.03**	**0.000**
Time x Treatment x Tidal height	**226**	**10**	**22**	**2.42**	**0.033**

Bold values indicate significant differences, $p<0.05$.

5.3.4.4 Mean abundances of five common species of the high- and mid-shore transect 2, 2002 compared to the upper- and high-shore 2003 wks 2 to 10

Tubificoides benedii and nematode colonization of the controls and treatment of the high- and mid-shores 2002 were significantly different to the upper- and high-shores 2003 over time similarly, the mean abundances of the five most common species significantly differed between treatment x tidal heights (Table 5.29). Significant interactions of time x treatment x tidal height occurred when comparing the colonization of *M. balthica*, *H. diversicolor* j and *T. benedii* at the high- and mid-shores 2002 with the upper- and high-shores 2003. Repeated contrasts revealed more complex significant interactions (Appendix 2 Table 5.29).

Table 5.29: Repeated measures ANOVA of five common species at the high- and mid-shores transect 2, 2002 controls and treatment 1 compared with the upper- and high-shores 2003 controls and treatment 2 from wks 2 to 10.

Source	SS	DF	MS	F	P
M. balthica					
Time x Tidal height	657	12	55	1.53	0.164
Treatment x Tidal height	**4141**	**4**	**1113**	**20.66**	**0.000**
Time x Treatment x Tidal height	**2301**	**24**	**96**	**2.17**	**0.007**
H. diversicolor j					
Time x Tidal height	779	6	129	1.52	0.234
Treatment x Tidal height	**726**	**6**	**121**	**7.23**	**0.001**
Time x Treatment x Tidal height	**1757**	**8**	**221**	**2.81**	**0.027**
P. elegans					
Time x Tidal height	3160	3	1004	0.57	0.655
Treatment x Tidal height	**25608**	**3**	**8124**	**70.58**	**0.000**
Time x Treatment x Tidal height	5429	3	1696	0.55	0.669
T. benedii					
Time x Tidal height	**148598**	**12**	**12383**	**4.28**	**0.000**
Treatment x Tidal height	**144847**	**6**	**24141**	**14.64**	**0.000**
Time x Treatment x Tidal height	**111049**	**24**	**4627**	**1.96**	**0.017**
Nematoda					
Time x Tidal height	**12900**	**12**	**1075**	**3.42**	**0.003**
Treatment x Tidal height	**4961**	**4**	**1342**	**3.83**	**0.041**
Time x Treatment x Tidal height	13848	7	1909	1.93	0.118

Bold values indicate significant differences, $p<0.05$.

5.4 Discussion

5.4.1 Sediment variables

The two mud treatments percentage water contents differed and treatment 1 had a higher water content (49.0 %) and was fluid in appearance, treatment 2 had a lower water content (39.0 %). However, the sedimentary characteristics of the experimental sediment treatments were not monitored for changes over time and the de-watering of the high-water content sediment treatment may have occurred. In comparison, the percentage water content of the defaunated control (34.0 %) and the natural mudflat control (33.0 %) were similar when sampled in years one (Chapter 4) and two and the water content of treatment 2 of this chapter was similar to the mud treatment (40.0 %) used in chapter 4. In contrast, the fine-grained dredged material used as sediment recharge for habitat enhancement/creation and the recharge areas of three beneficial use schemes located in estuaries of south-east England were higher in percentage water content than the sediments used in the present research. Westwick Marina, for example, sediment water content ranged from 91.2 % to 66.5 %, Titchmarsh Marina sediments ranged from 91.7 % to 60.6 % and North Shotley from 60.3 % to 55.2 % (Bolam and Whomersley, 2005). However, the more fluid treatment used in this chapter was most similar in water content to the sediments at North Shotley. In comparison, Widdows, *et al.*, (2006) investigated the temporal changes of biota and sediment erodability following the deposition of fine-grained dredged material at two beneficial use schemes: Westwick Marina and Titchmarsh Marina both situated on the upper-shore area of intertidal shores of estuaries in Essex, UK. Following the placement of dredged material a rapid de-watering and consolidation of the recharge sediments placed at the Westwick Marina and Titchmarsh Marina occurred within 7 days, thereafter the water content generally decreased with time from 86.0 % and 90.6 % respectively following 4 hours post-recharge to 60.9 % and 51.4 % respectively in April 2002 (Widdows, *et al.*, 2006). Other sedimentary characteristics of the recharge material varied with time, Widdows, *et al.*, (2006) noted a fluctuation of carbon content at the Westwick Marina and Titchmarsh Marina from 8.4 to 4.2 % and 6.7 to 4.2 % respectively. This was higher than the carbon content of the experimental sediment treatments used in the current study. They also noted changes of sediment erodability were correlated with the nature of the benthic assemblage of the re-colonized recharge areas. For example, species that are known ecosystem engineers such as *Corophium volutator* (Pallas), *H. diversicolor* and *H. ulvae* had a functional role as bio-destabilisers whilst tube dwelling polychaetes and oligochaetes were bio-stabilisers.

5.4.2 Macro-faunal colonization from the water column

5.4.2.1 Univariate recovery

The sampling of macro-faunal communities over a 10-week period of the present study, in addition to a previous 17-week study period enables the evaluation of spatial and temporal changes in colonist communities. The implementation of a high-water content mud treatment in this study in addition to a previously utilized lower-water content mud treatment demonstrated a rich and diverse macro-faunal assemblage was present within 10-weeks. Indeed, total macro-faunal densities of mud treatments placed at the upper-shore were similar to natural mudflat and defaunated control levels. This rapid re-colonization within a 3-month period has been observed during the re-colonization of previously studied beneficial use schemes, an example being the Westwick Marina (Bolam and Whomersley, 2003; Bolam, *et al.*, 2006). However, the present study shows the species richness of the high-water content mud treatment remained dissimilar to the natural mudflat level of the upper-shore. In contrast, the high-shore had a much greater total macro-faunal density than the upper-shore being almost twice as large. In comparison, the previous years high-shore total macro-faunal densities were similar and both were greater than the high-shore macro-faunal re-colonization of this study. The study conducted in 2002 (Chapter 4) was longer in duration than this study (by three weeks) thus, allowing more time for invertebrate recovery, although both were started during the spring period. However, the upper-shore total macro-faunal density provided by this study was greater than the observed densities of the upper-shore previously studied in Chapter 4.

As shown here, this study reveals a greater species richness at the upper-shore in comparison to those species colonizing the high-shore mud treatments. Species richness of this study was approximately a third less than observed at the Titchmarsh Marina beneficial use scheme, following 42-months of recovery (Bolam, *et al.*, 2006). The total macro-faunal densities of the high-shore mud treatments were significantly greater than the natural mudflat levels. However, density significantly decreased in the mudflat control from the middle to the end of May when compared to the mud treatments. Total macro-faunal densities of the high-shore mud treatments were similar to the defaunated control levels. Additionally, the species richness of the lower-water content sediment treatment was significantly greater than the defaunated control and species richness significantly increased over time from the end of April to the middle of May. In comparison, the total macro-faunal density, species richness and diversity of a recharge site at the Titchmarsh Marina failed to converge towards that of a reference site following a 42-month recovery period, due to natural spatial heterogeneity between the recharge and reference sites (Bolam, *et al.*, 2006). In addition, the number of species colonizing the recharge site located at the Westwick Marina was significantly lower than the reference site following 12 months of recovery (Bolam and Whomersley, 2004).

5.4.2.2 Species re-colonization

The re-colonization of the experimental sediment treatments occurred rapidly in the present field study. Some taxon including *T. benedii*, *H. diversicolor* (both adult and juvenile life stages), *S. shrubsolii* and nemtodes, were common at both tidal heights while other species more dominant at the upper-shore include Enchytraeidae, *M. aestuarina*, *P. elegans*, *H. ulvae*, *P. litoralis* and at the high-shore; *M. balthica* and juvenile Tellinacea. Statistical analysis revealed there were no significant differences between the comparisons of the defaunated control to different macro-faunal species re-colonization of the mud treatments at the upper-shore.

At the high-shore, the re-colonization of the low-water thin layer sediment treatment by *M. balthica* was significantly greater when compared to the distribution in the defaunated control. Significant changes in re-colonization occurred over time when comparing its ability to colonize the treatments and the mudflat control and a significant decrease in overall colonization occurred from the middle to the end of May. In contrast, other estuarine bivalve species such as *Scrobicularia plana* (da Costa) successfully colonized an impacted area following one year of a pipeline construction at Clonakilty Bay, West Cork, Ireland, where the re-colonization was mostly attributed to the settlement of juveniles (Lewis, *et al*., 2003). In this study the recovery of juvenile Tellinacea at the high-shore was significantly less in the high-water thin layer sediment treatment than the mudflat control. Therefore the ability of estuarine bivalves to colonize the thin layer depositions of sediment treatments to a total depth of 10 cm in this study did not reach natural mudflat levels over a recovery period of 10 weeks and longer-term colonization would be necessary to facilitate the recovery of intertidal estuarine bivalve densities. In contrast, the effects of thin layer sediment depositions of fluid terrigenous clay was investigated as a field experiment in New Zealand. Norkko, *et al*., (2006) examined the response of two estuarine soft-sediment bivalves to increased sedimentation over varying temporal scales. They used nucleic acid ratios to determine any adverse effects to bivalve growth following thin layer sediment deposition and found no significant effects in the short-term but noted longer-term changes did occur.

The re-colonization of *H. diversicolor* significantly differed over time at the upper- and high-shore when comparing the treatments with the mudflat control following 10-weeks of recovery. Initially, the mudflat levels and colonization of the treatments was low and a general increase of abundance began from the middle of May 2003 onwards. A similar pattern emerged when comparing *H. diversicolor* colonization of the treatments in comparison to the defaunated control at the high-shore and a significant increase in overall colonization occurred over time. *Hediste diversicolor* is an errant polychaete species, actively burrowing into the mud profile and swimming in the water column, its main spawning phase is at its highest during the spring period of March/April, spawning activity is reduced during the remainder of the year (Rasmussen, 1973). Therefore, mature adult individuals may become more active in seeking prey and/or immigrating to other areas to exploit new resources following the recruitment phase. The thin layer sediment depositions began in April 2003 and were colonized by juvenile immigrants; significantly more juvenile *H. diversicolor* colonized the high-shore thin layer sediment treatments than the mudflat control.

Mechanisms used to observe re-colonization in comparable literature can differ somewhat in methodologies. For instance, Levin (1984) studied the spatial and temporal recruitment patterns of a dense infaunal polychaete assemblage on the Kendall-Frost mudflat in Mission Bay, southern California. Over a period of three years the recruitment of several polychaete species was monitored by placing defaunated sediments into settling trays (9 x 9 x 9 cm) positioned 7 cm above the mudflat surface, each tray contained 7 cm of defaunated mud and the trays were enclosed in mesh wire cages for two week periods, the settlement of recruits from the water column was the colonization mechanism of the experiment; the recruits were later retained on a 250 μm mesh. In the present study, the immigration of macro-fauna was investigated using PVC tubes secured into the mudflat, a parafilm barrier was inserted into tube to prevent any vertical migration from the mudflat, each microcosm was positioned above the mudflat surface, thus ensuring that the route of immigration was from the water column and not from the surface horizontal migration of individuals from adjacent mudflat areas, also in the present study the recharge material was added in small amounts over time, Levin (1984) placed a single deposition of mud to a depth of 7 cm.

Similarly, the primary mechanism of macro- and meio-faunal re-colonization of beneficial use schemes was through the settlement (actively and/or passively) (Schratzberger, *et al.*, 2006) of planktonic larvae or post-larval juveniles from the water column (Bolam and Whomersley, 2003, 2005; Bolam, *et al.*, 2006). However, not all polychaete species share the same dispersal mechanisms; therefore some species do not include a planktonic recruitment phase, for example, Levin (1984) noted *Fabricia limnicola* (Hartman) absence from settling trays and its inability to enter the water column. However, Levin (1984) noted other polychaete species such as *Pseudopolydora paucibranchiata* (Okuda), *Polydora ligni* (Webster) and *Rhynchospio arenincola* (Hartman) were common recruits in the settling trays due to a planktonic larval development stage, other species included *Prionospio malmgreni* (Claparedc), *Eteone dilatae* (Hartman), *Capitella* spp. and *Nereis* sp. whilst some polychaete species colonized the trays as body brooders, for example, *P. paucibranchiata*, *Streblospio benedicti* (Webster) and *Exogone lourei* (Hartman), as did nematodes.

In the current study, the opportunistic oligochaete group were the most prolific colonizers. In order of dominance there were *T. benedii*, Enchytraeids and the Naid *P. litoralis*, unlike the previous years study when *T. benedii* was the only oligochaete species recorded. *Tubificoides benedii's* reproductive mechanism lacks a planktonic larval dispersal stage; instead it remains below surface and uses asexual reproduction as a type of reproductive strategy. At the high-shore it was noted that the colonization of *T. benedii* was significantly higher in both thin layer sediment treatments when compared to the mudflat control, in addition the densities distributed within the sediment treatments were similar to the defaunated control. The mechanism of re-colonization may have been via passive and/or active transport in the water column, as other oligochaete species such as *P. litoralis* have been known to swim (Nilsson, *et al.*, 2000). Therefore, *T. benedii* clearly demonstrates the ability to successfully colonize both high- and lower-water sediment treatments when deposited at the high-shore as repeated thin layers or when more consolidated defaunated sediment was deposited. This supports the findings of Bolam, *et al.*, (2006), who concluded that once the colonization of the recharge material or defaunated sediments begins, temporal changes see an increase of macro-faunal abundance as colonization from the water column continues and reproduction of settled adult macro-fauna takes place. In contrast, Enchytraeidae colonization of the sediment treatments at the upper-shore was high initially but gradually decreased over time and did not significantly differ to the controls with significantly fewer colonizing the high-shore area or treatments. Similarly, few *P. litoralis* colonized the high-shore area or the sediment treatments and at the upper-shore the treatment densities remained dissimilar to the natural mudflat levels.

More recently, Junkins, *et al.*, (2006) conducted oligochaete migration experiments in a soft-sediment environment at southern New England and New York mudflats using settlement dishes. The dominant oligochaete species was *P. litoralis* both the emigration and immigration of this species fluctuated and was dependent on the density of the ambient population and abundance of food resources. This example demonstrates that when the population density is high the food source became reduced, budding frequency declined and emigration of longer individuals increased. Nilsson, *et al.*, (2000) found that swimming *P. litoralis* are longer and thinner than non-migrating individuals and are more likely to swim when food resources are exhausted. Also, the ability of swimming *P. litoralis* to remain in the water column was greater than non-migrating individuals. Laboratory experiments have shown that individuals will swim to areas that are nutrient rich whilst resource depleted sediments are avoided (Nilsson, *et al.*, 2000). Experiments by Junkins, *et al.*, (2006) included emergence and settlement traps placed into an area of mudflat, the emigrating *P. litoralis* were trapped in a conical flask fixed into a piece of PVC pipe, whilst immigration from the water column was investigated using Petri dishes attached to a sheet of plexiglass. The colonization trays were filled with an experimental sediment treatment of defaunated mud. Each experimental period was 4 days, thus reducing the chances of colonization through the reproduction of immigrants; the experiments began in the spring until late summer for two years. They found a significant interaction between time and site when *P. litoralis* settled from the water column. In addition, the number of swimming and settled individuals peaked during May 2004 then decreased over the summer.

In contrast, the recovery of the nematode assemblage was significantly less in both thin layer sediment treatments when compared to the mudflat control and densities remained dissimilar to the natural mudflat levels following 10 weeks of recovery. The suggestion that the colonization mechanism of nematodes in the present study is likely to be via the random settlement of suspended individuals in the water column (as other routes of colonization were excluded). This was also demonstrated by Schratzberger, *et al.*, (2006) during a study investigating the re-colonization potential of nematode assemblages on fine-grained dredged material over a 12-month period at North Shotley, along the Orwell Estuary. They demonstrated that the nematode colonist community at four different sites occurred as a result of randomly settled suspended nematodes in addition to the reproduction success of colonizing species. Similarly, a field study using manipulated sediments at an intertidal estuarine mudflat showed that the nematode component of manipulated sediment organic content treatments remained different to the natural community of an adjacent mudflat following a 12 month study (Schratzberger, *et al.*, 2004 a).

5.4.2.3 Spatial and temporal differences in treatment colonization

During the current study, a number of significant spatial differences were highlighted between tidal heights. For example, the total macro-faunal densities were significantly different over time when comparing the upper- and high-shore treatments with the controls, with significantly more individuals colonizing the high-shore microcosms. Conversely, species richness was significantly different in the manipulated low-water sediment treatment when compared to the defaunated control between tidal heights, significantly more species colonized the upper-shore manipulated low-water sediment treatment and defaunated control than the high-shore.

There was a significant difference in *H. diversicolor* colonization of the low-water sediment treatment when compared to the defaunated control between tidal heights. Also, *H. diversicolor* colonization was significantly greater in the low-water treatment than the defaunated control at the upper-shore on more sampling occasions than the high-shore. In addition, more individuals colonized the high-shore high-water sediment treatment in contrast to the natural mudflat level when compared to the upper-shore. *Tubificoides benedii* colonized the high-shore sediment treatment microcosms and mudflat more than at the upper-shore. Additionally, significant interactions of nematode colonization occurred between tidal heights but overall equal densities occurred at the upper- and high-shore.

The colonization of the low-water treatment type used in this study (2003) at the high-shore was compared to the previous year's (2002) colonization experiment from weeks 2 to 10. Significant differences occurred in the total macro-faunal densities between the years with more individuals (approximately a third more) colonizing the manipulated low-water sediment treatment in 2003 than during 2002. However, the natural mudflat densities of macro-fauna were approximately a third higher during 2002 than 2003. In contrast, the number of species colonizing the low-water treatment type and controls at the high-shore did not significantly differ between years. In addition, the total densities of *M. balthica* and *T. benedii* in the low-water treatment and mudflat control significantly differed between years. The mean densities of *T. benedii* were greater in the low-water treatment when compared to the mudflat control conversely, the previous years mean densities were greater in the mudflat control than the low-water treatment.

5.4.3 Factors affecting macro-faunal colonization

The macro-faunal re-colonization of the upper-shore treatments and controls did not show any significant correlations with any sedimentary characteristics, although *H. diversicolor* and *T. benedii* were positively correlated with time and a gradual increase of abundance occurred following 4 weeks of recovery. Some species were negatively correlated with time, for example, *M. aestuarina*, *P. litoralis* and Enchytraeids. Mean abundances of Enchytraeids and *P. litoralis* were greatest during the early stages of the study but a decrease in colonization occurred over time. In contrast, to the upper-shore species correlations with time, of the species colonizing the high-shore treatments and controls only *H. diversicolor* was positively correlated with time and like the upper-shore, colonization increased from week 4 of the study onwards.

Other species colonizing the high-shore such as *M. balthica,* juvenile Tellinacea, *P. elegans*, *S. shrubsolii* and nematodes were negatively correlated to time. Juvenile Tellinacea, *P. elegans* and nematodes were early colonizers but decreased in abundance over time. Overall, *T. benedii* was the only species to show a sediment-associated pattern and was positively correlated to the sediment water content and negatively correlated to percentage dry weight when colonizing the high-shore. Mean densities were greater in the manipulated sediment water content treatments than the natural mudflat levels. Therefore, the deposition of high-water content fine-grained simulated dredged material when placed at the upper- or high-shore did not inhibit macro-faunal recovery. Other studies recorded an association between colonizing adult *M. balthica* individuals and a muddy treatment and an association between colonizing adult *C. edule* individuals with a sandy substratum (Huxham and Richards, 2003). Like the present study, Huxham and Richards (2003) noted that smaller size classes of bivalves did not demonstrate any sediment-associated patterns.

As shown here, when simulated fine-grained dredged material was deposited as smaller multiple amounts of 2 cm over a succession of weeks, the mudflat height was slowly recharged and allowed to build up over time to a sediment depth of 10 cm, this facilitated the gradual macro-faunal re-colonization of the recharge material over the summer period. A conceptual model of multiple depositions of manipulated sediment was constructed and macro-faunal community response was compared in the general discussion (Chapter 6).

5.4 Conclusions

1. **Sediment characteristics:** The high-water sediment treatment was similar in water content to the recharge dredged material deposited at the North Shotley beneficial use scheme but was lower in water content than material used at other beneficial use schemes such as the Westwick and Titchmarsh Marinas.
2. **Univariate recovery:** The implementation of a high-water content mud treatment as thin layer depositions to a total depth of 10 cm in this study in addition to a previously utilized lower-water content mud treatment demonstrated a rich and diverse macro-faunal assemblage was present within 10-weeks:
   i. The total macro-faunal density of the treatments at the high-shore was significantly higher than the ambient mudflat level.
   ii. The total macro-faunal density of the high-shore treatments did not significantly differ to the defaunated control.
   iii. Species richness at the high-shore high-water content treatment was significantly higher than the defaunated control.
   iv. Species richness of the upper-shore was greater than those colonizing the high-shore treatments. However, numbers colonizing the low-water content treatment were significantly less than the natural mudflat level. Significantly more species colonized the upper-shore low-water treatment and defaunated control than the high-shore.
   v. Significantly more individuals colonized the high-shore microcosms when compared to the upper-shore.
3. **Good colonizers:**
   i. *Tubificoides benedii* exhibited a good ability to colonize both high- and low-water content sediment treatments when deposited at the high-shore as repeated thin layers or when more consolidated defaunated sediment was deposited.
   ii. The thin layer sediment depositions began in April 2003 and were colonized by post-larval immigrants and significantly more juvenile *H. diversicolor* colonized the high-shore thin layer sediment treatments than the mudflat control. From the middle of May onwards, adult *H. diversicolor* successfully colonized the sediment treatments.
4. **Poor colonizers:**
   i. The ability of estuarine bivalves such as *M. balthica* and juvenile Tellinacea to colonize the thin layer depositions of sediment treatments to a total depth of 10 cm in this study did not reach natural mudflat levels over a recovery period of 10 weeks.
   ii. The recovery of the nematode assemblage was significantly less in both sediment treatments when compared to the mudflat control.
5. **Temporal variation:**
   i. At the high-shore, significantly more individuals colonized the low-water content mud treatment in 2003 than during 2002, however the natural mudflat densities of macro-fauna were greater during 2002 than 2003.
   ii. The number of species colonizing the low-water content mud treatment type and controls at the high-shore did not significantly differ between years.

iii. The mean densities of *T. benedii* in the low-water content mud treatment and mudflat control significantly differed between years. The mean densities of *T. benedii* were significantly greater in the low-water sediment treatment when compared to the mudflat control at the high-shore 2002. Conversely, the previous years mean densities were greater in the mudflat control than the low-water content mud treatment.

6. **Factors affecting macro-faunal colonization of the upper- and high-shore, 2003:**
   i. The macro-faunal re-colonization of the upper-shore treatments and controls did not show any significant correlations with any sedimentary characteristics, although *H. diversicolor* and *T. benedii* were positively correlated with time and a gradual increase of abundance occurred following 4 weeks of recovery. In contrast, some species were negatively correlated to time, for example, *M. aestuarina*, *P. litoralis* and Enchytraeids. Mean abundances of Enchytraeids and *P. litoralis* were greatest during the early stages of the study but a decrease in colonization occurred over time.
   ii. At the high-shore only *H. diversicolor* was positively correlated with time and colonization increased from week 4 of the study onwards. *Macoma balthica*, juvenile Tellinacea, *P. elegans*, *S. shrubsolii* and nematodes were negatively correlated with time. Juvenile Tellinacea, *P. elegans* and nematodes were early colonizers but decreased in abundance over time.
   iii. *Tubificoides benedii* was the only species to exhibit a sediment-associated pattern at the high-shore and was positively correlated to the sediment water content and negatively correlated to percentage dry weight and mean densities were greater in the manipulated sediment water content treatments than the natural mudflat levels.
7. When simulated fine-grained dredged material was deposited as small multiple amounts over time, the mudflat height was recharged and allowed to build up. Consequently, the gradual macro-faunal re-colonization of the recharge material occurred over time. Therefore, the deposition of high-water content fine-grained simulated dredged material when placed at the upper- or high-shore did not inhibit macro-faunal recovery. A conceptual model of manipulated sediment depositions was constructed (Chapter 6) and macro-faunal community response of this study was compared with Chapters 3 and 4.

6 General Discussion

There are two main methods to evaluate the recovery of a created habitat, the first method uses measures of community structure such as total macro-faunal densities, species richness and diversity indices (Levin, *et al.*, 1996) whilst the second assesses the functional similarities of a newly created habitat with a natural one, for example, the species composition. The former was used in the present research. The results indicate that invertebrate community recovery of fine-grained sediment experimental treatments can occur rapidly, for example, within 17 weeks following thin layer sediment depositions. These findings support those of Bolam and Whomersley (2003) where the rapid re-colonization of a fine-grained beneficial use scheme at the Westwick Marina, along the Crouch Estuary, Essex occurred following 3 months post placement of the recharge material.

In other studies examining invertebrate re-colonization of defaunated sediment plots, Beukema, *et al.*, (1999) noted that the univariate recovery occurred following three summers. Thrush, *et al.*, (1996) also examined the recovery of macro-fauna in defaunated sediment plots but on a sandflat in New Zealand. However, in this study the univariate recovery was not achieved and numerical indices had not recovered to a predefined value following a nine-month study.

6.1 Macro-faunal colonization mechanisms and recovery rates

Determining the relative importance of infaunal species colonization mechanisms is essential for predicting changes in benthic communities following disturbance (Santos and Simon, 1980; Levin, 1984; Smith and Brumsickle, 1989; Shull, 1997; Ford, *et al.*, 1999). Several colonization methods possible within a beneficial use scheme were studied here including benthic macro-faunal settlement, burrowing and post-larval movement through swimming (Figure 6.1).

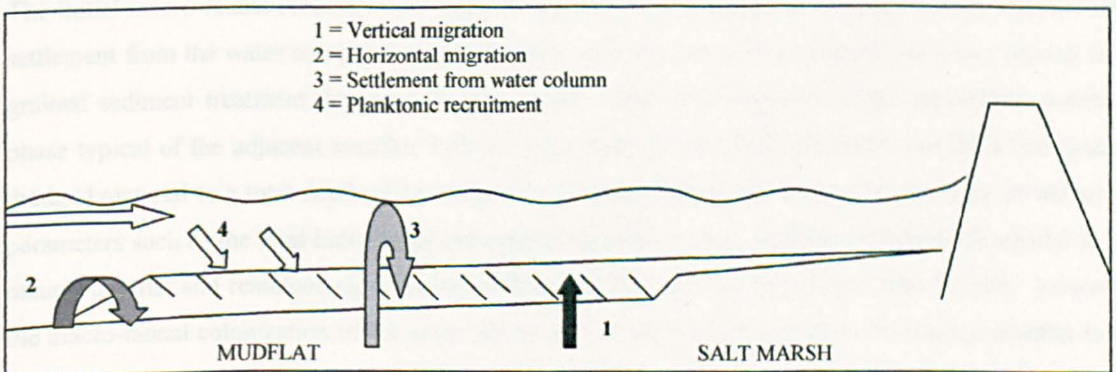

Figure 6.1: Macro-faunal recovery mechanisms following intertidal placement of dredged material (modified from: Bolam, *et al.*, 2003).

6.1.1 Macro-faunal vertical migration

Some degree of infaunal recovery occurred in the 10, 15 and 20 cm depth mud and sand sediment treatments when an aquarium microcosm experiment was implemented over a period of 2.5 months and the primary re-colonization mechanism was through infaunal vertical migration. The total mean infaunal abundances of most sediment treatments remained lower than the control except when a single deposition of sand treatment to a depth of 10 cm was applied. Additionally, the mud treatments had the greatest species richness followed by the control and the sand treatments and the high deposition treatments of mud were more diverse than the low frequency depositions. A poor short-term recovery of vertically migrating infaunal species occurred when manipulated fine-grained sediment treatments were deposited in field microcosms for a period of 4 months. However, the initial number of colonizing species was high and exceeded the species richness in the initial mudflat situation. Similarly, species diversity and evenness in the mud treatment was generally equal to or greater than the initial mudflat situation. However, this study was conducted during the winter period when temperatures were reduced and conditions less favourable for infaunal migration.

6.1.2 Macro-faunal horizontal migration

A second winter field experiment designed to investigate the ability of infaunal mudflat species to horizontally migrate into manipulated fine-grained sediment revealed that the short-term recovery had significantly begun to increase following 28 days of recovery but did not exceed the initial mudflat total abundance. In contrast, the number of species that horizontally migrated into the treatment following 13 and 28 days exceeded the number present in the initial mudflat situation.

6.1.3 Macro-faunal colonization from the water column at different tidal heights

The initial macro-faunal recovery was rapid during further field experiments investigating macro-faunal settlement from the water column at spring/summer temperatures onto a manipulated water content fine-grained sediment treatment deposited in thin layers. Recovery remained in the opportunist-dominant phase typical of the adjacent mudflat, following the multiple thin depositions of simulated fine-grained dredged material to a total depth of 14 cm over a 17-week period. Over time the recovery of univariate parameters such as the total individuals and species richness in most instances remained dissimilar to the natural mudflat and remained significantly different at the high- and mid-shore tidal heights. However, the macro-faunal colonization of the upper-shore mud treatment was similar to the natural mudflat level. The community analysis revealed a similarity between the communities of the mud treatment and controls in late April suggesting the initial stages of macro-faunal recovery at the high-shore were similar. Additionally, the recovery of total individuals and species richness differed between tidal heights and were greater at the high-shore when compared to the upper- and mid-shore areas. Overall, the high-shore was the most productive in terms of biomass yielded from the mud treatment and defaunated control followed by the mid- and upper-shores experiments.

In addition to a previously utilized lower-water content mud treatment described above, a further field study investigated the macro-faunal colonization from the water column onto a high-water content mud treatment deposited as thin layers to a total depth of 10 cm. A rich and diverse macro-faunal assemblage was present within 10-weeks at the high-shore sediment treatments and univariate parameters such as total individuals and species richness exceeded the mudflat level. Additionally, the total macro-faunal density of the treatments did not significantly differ to the defaunated control. When sediment microcosms were placed at the upper-shore the number of species colonizing the low-water content mud treatment remained different to the natural mudflat. However, significantly more individuals colonized the sediment microcosms when placed at the high-shore.

6.2 Simulated dredged material deposition model

Elliott, *et al.*, (2000) constructed a conceptual model of the fate and effects of mud-spoil input to benthos (Figure 6.2). They suggested a mud sediment deposition placed onto a receiving area of mud would result in a slight disturbance, this in turn would provide a chance for opportunistic species to colonize the newly deposited material. As a result the macro-faunal community response would be high in terms of recovery. For example, species richness and abundance would not be adversely affected in the long-term and an equilibrium would be regained. In general, the present research supports the findings of Elliott, *et al.*, (2000) and allowed a modified conceptual model of the simulated dredged material deposition onto an estuarine mudflat to be developed (Figure 6.3). In contrast to Elliott, *et al.*, (2000), the findings of Chapter 3 show that when an amount of simulated dredged material was deposited onto the mudflat as a single larger amount of material of 27 cm and 50 cm during a winter period for 2.5 months, a low abundance of horizontally and vertically migrating macro-fauna occurred and a poor recovery was recorded (Figure 6.3). Conversely, when an amount of simulated dredged material of a higher water content was deposited onto the mudflat as smaller multiple amounts spread over 10 and 17 weeks, the community response was better when depositions occurred during the spring-summer period than in the winter. For example, at the high-shore the species richness was moderate and abundance was high and colonization increased when sediment depositions occurred during the spring-summer. Also, when multiple sediment veneers were placed at the upper-shore the community response was equally good and diversity was high following manipulated sediment depositions. Additionally, if the deposition of a sediment type differs to the receiving area substratum type this can change the original macro-benthic community (Figure 6.2). The present studies used a fine-grained sediment type in all experiments apart from the aquarium experiment of Chapter 2 when an additional sand sediment type was deposited onto mudflat cores as a single larger deposition amount or as smaller thin veneers.

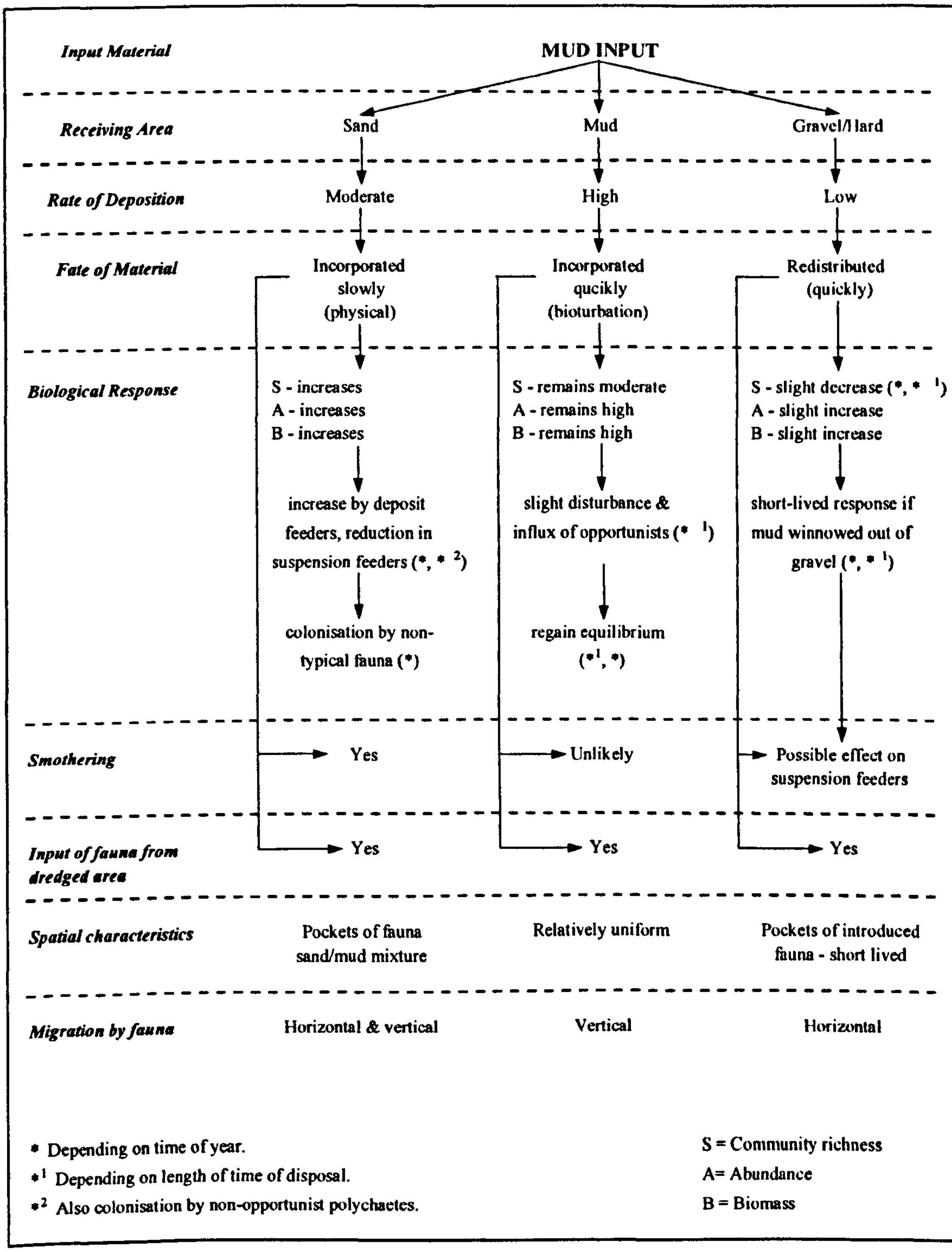

Figure 6.2: Proposed conceptual model fate and effects of mud-spoil input to benthos (Elliott, *et al.*, 2000).

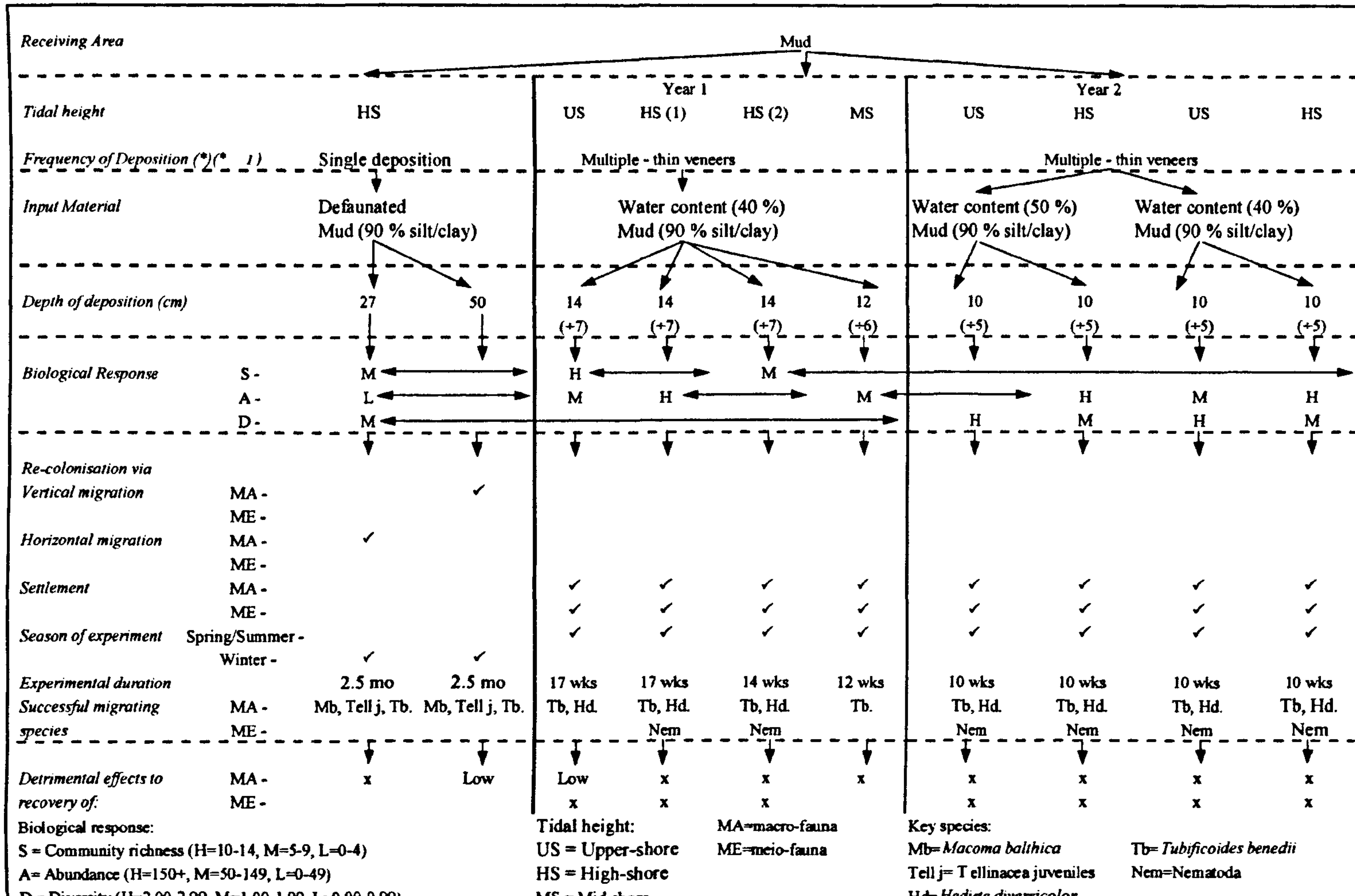

Figure 6.3: Conceptual model of macro-zoobenthic colonization of mud treatments deposited at different tidal heights of a mudflat. (Depending on: * time of year, *1 duration of disposal.)

6.3 Species re-colonization

The re-establishment of a community can occur within a few months of a disturbance, as shown during the present thin layer sediment deposition experiments. Other studies have shown that macro-faunal recovery can take longer, for example, six months after completion of a dredging project, the macro-benthos of a dredged area in NW Spain had recovered (Lopez-Jamar and Mejuto, 1988). However, the complete recovery of wetland habitats can take several years (Levin, *et al.*, 1996; Posey, *et al.*, 1997: Swamy, *et al.*, 2002). In another marine habitat study, Harvey, *et al.*, (1998) noted that the full recovery of a macro-benthic community structure and sediment composition took two years at an open-water disposal site in Eastern Canada. As shown in the present study, the densities of benthic taxa such as the polychaete *H. diversicolor* are an important food source for shorebirds and were restored following 4 months of recovery. The opposite effect occurred following three years of mudflat restoration and densities of benthic taxa such as *H. diversicolor* and the amphipod *C. volutator*, were still lower than those in natural the mudflat (Evans, *et al.*, 1998). In the current studies, a low number of *C. volutator* colonized the field experiments and the natural mudflat making statistical analysis difficult.

As shown here, if the recharge site is small or has a mosaic of colonized areas, then re-colonization would be more favourable. Successful colonizers may be adapted to stress and recover quickly from frequent episodes of burial. The rapid recovery of an area of newly deposited material can occur due to an influx of opportunistic species (Bonsdorff, 1980). Opportunistic or early-colonizing species density usually follows an inter-annual pattern. Unexploited or disturbed sediments are favoured by opportunists and are typically r-strategists and are present in high abundance (Hall, 1994), have a high reproductive rate and/or a high dispersal ability (Grassle and Grassle, 1974), reach early sexual maturity and are short-lived. Minello (2000) suggests that some infaunal densities recover, as they are opportunists. The main opportunistic polychaete families of the current studies were Nereidae and Spionidae. Similary, Harvey, *et al.*, (1998) recorded Nereidae, Phyllodocidae and Spionidae as opportuntistic polychaete families. Furthermore, the presence of tube-dwelling polychaetes can stabilize sediments and facilitate colonization by other species (Gallagher, *et al.*, 1983, Neumann and Scoffin, 1970 in: Brey, 1991). As shown here, the tube dwellers *P. elegans* and *S. shrubsolii* colonized each experiment. Other early-colonizers of the present studies included *T. benedii*, *M. balthica* and juvenile Tellinacea. In comparison, other studies recorded *H. ulvae*, the amphipod *Gammarus oceanicus* and *T. benedii* during the early stages (Ray, 2000). Leathem, *et al.*, (1973) observed a post-disposal recruitment of bivalves, at a disposal site in the Delaware Bay and the abundance of some dominant species remained the same at a disposal site in Hawkesbury Estuary, Australia. For example, the polychaete *Terebellides stroemi* (Sars) and the amphipod *Grandidierella gilesi* (Chilton), as burial tolerance and survival rates were high (Jones, 1986). Evans, *et al.*, (1998) concluded that as colonization by prey species increased at a re-created mudflat site, the amount of bird feeding activity increased. The amount of bird feeding activity was not recorded in the present studies.

As shown here, an increase in the density of opportunistic species occurred shortly after the deposition of simulated dredged material, Rhoads, *et al.*, (1978) observed similar following dredged material disposal. However, the rates of macro-faunal recovery may differ between species, for example, in a seasonal study the full recovery of adult stages of *Arenicola*, *Nereis* and *Harmothoe* species in defaunated sediment plots at the Wadden Sea did not occur until the end of the third summer (Beukema, *et al.*, 1999). The re-colonization by benthic fauna of a previously defaunated intertidal areas were examined by Dauer and Simon (1976 a; 1976 b) and during *in situ* substrata manipulation experiments (Diaz-Castaneda, *et al.*, 1993; Turner, *et al.*, 1997; Bolam, 1999; 2000 c; 2002). Sediment defaunation of treatment material was achieved by sieving (Olafsson, 1988), sieving followed by dehydration (Maurer, *et al* 1980-81; 1981; 1982), freeze-thaw processing (Bolam, 1999; 2000 c; 2002; Schratzberger, *et al.*, 2000), chemically removing organic matter using hydrogen peroxide (Grant, *et al.*, 1997) or insecticide dispersal (de Deckere, *et al.*, 2001). Harvey, *et al.*, (1998) suggested that the availability of a new food supply, present within deposited dredged material could facilitate an increase of faunal density. Also, there is little competition in dredged areas (Lopez-Jamar and Mejuto, 1988); therefore defaunated material colonization would be quicker.

6.3.1 Macro-faunal vertical and horizontal migration

The aquarium experiment of Chapter 2 showed the importance of species colonization from below, for example, *M. balthica* and *T. benedii* vertically migrated up into 20 cm of fine-grained sediment when deposited in high or low frequencies and were widespread in distribution. *Pygospio elegans* vertically migrated to the surface layers of a 10 cm depth fine-grained sediment overburden when deposited as low or high frequencies. These results suggest that *P. elegans* had a low ability to migrate vertically into the surface layers of low- or high-frequency depositions of mud when an overburden amount exceeds 10 cm. In comparison, few Nephytyidae and Opheliidae polychaete individuals were able to re-colonize a sediment disposal site by vertical migration (Harvey, *et al.*, 1998). A further change was experienced in the feeding mode of polychaete families, from a pre-disposal carnivorous population to a post-disposal increase of motile subsurface and surface deposit feeding opportunistic polychaete families of Cossuridae, Spionidae, Paraonidae and Capitellidae (Harvey, *et al.*, 1998).

In the winter field experiment of Chapter 3 some species were rapid colonizers of the defaunated mud treatment, such as *M. balthica* and juvenile Tellinacea and vertically migrated to reach the surface layers of a 50 cm fine-grained sediment overburden when deposited as a single amount and were present after two weeks. *Tubificoides benedii* individuals were slower to colonize the surface of a 50 cm fine-grained sediment overburden but reached the upper sediment layers after six weeks of burial. Therefore, *M. balthica*, Tellinacea j and *T. benedii* exhibited some ability to vertically migrate throughout a fine-grained sediment overburden of 50 cm at winter temperatures. The re-colonization of sediment treatments via the below surface horizontal migration of macro-fauna occurred when 27 cm of fine-grained sediment treatment was placed at the field site during the winter. Again the main macro-faunal colonizers of the field experiment of Chapter 3 were *M. balthica*, Tellinacea j and *T. benedii* exhibiting some ability to horizontally immigrate into deposited mud treatment at winter temperatures.

6.3.2 Macro-faunal settlement from the water column

The present macro-faunal settlement studies were conducted from April onwards to include the main recruitment phase and the sediment microcosms were trickle charged over the summer with fluid mud treatments. The most successful colonizing species at three different tidal heights were the opportunist oligochaete *T. benedii* and both adult and juvenile *H. diversicolor*. Bolam and Whomersley (2003) also noted the predominant recovery process at a beneficial use scheme at the Westwick Marina was via active post-juvenile immigration. In the present study some species were poor colonizers of the fluid mud treatments and the number of estuarine bivalves such as *M. balthica* and juvenile Tellinacea to colonize the thin layer sediment depositions to a total depth of 10 cm did not reach the adjacent mudflat control abundances over a recovery period of 10 weeks. Also, the number of nematodes in the fluid mud treatments were significantly less than in the adjacent mudflat cores. Other studies have demonstrated that fluid mud could be colonized by macro-benthic infauna in response to sediment disturbance caused by the deposition of large quantities of fluid mud. For example, when fluid mud was deposited in a tidal freshwater system such as the James River, Virginia, USA; the primary colonization mechanism route was via adult immigration from surrounding areas (Diaz, 1994). Estuaries may be very stressed environments. This is reflected in the nature of the benthic invertebrate communities of intertidal mudflats, which have a high resilience to sediment disturbance (Bolam and Rees, 2003). The anthropogenic activities creating large-scale physical disturbances of soft-bottom communities can be compared to those caused by the hydrodynamics of an area (Brey, 1991) (Figure 6.4). The intensity of sediment disturbance can vary and may depend on the nature of the method employed to disperse the sediment, for example, if beach nourishment in an area created a higher level of disturbance.

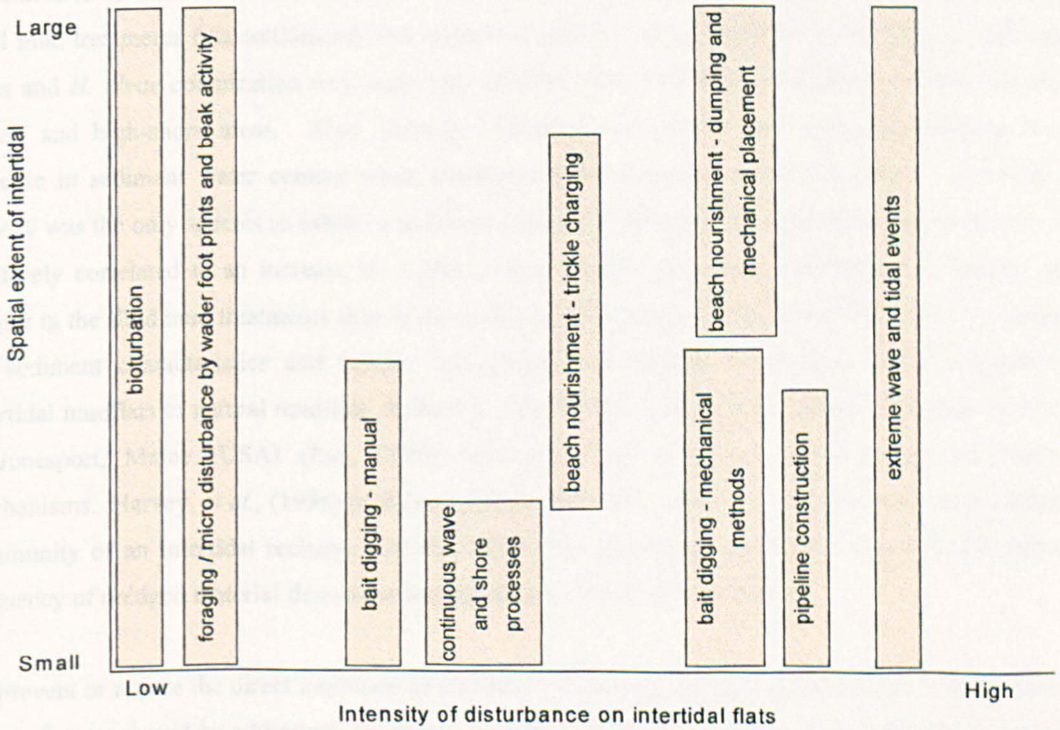

Figure 6.4: A conceptual model of spatial and temporal changes to sediments based on information researched for Elliott, *et al.*, (1998; 2000).

In general, when simulated fine-grained dredged material was trickle-charged slowly, this allowed the gradual macro-faunal re-colonization of the recharge material over time. Therefore, the deposition of high water content fine-grained simulated dredged material when placed at the upper- or high-shore did not inhibit general macro-faunal recovery. In contrast, other studies revealed the biological and environmental parameters are reduced. There may be a reduction of species of less opportunistic families such as polychaetes species of Nephtyidae and Opheliidae, crustacea of Ampeliscidae, Melitidae, Oedicerotidae, Leuconidae and Isaeidae (Harvey, *et al.*, 1998) and hence the recharge area will become dominated by highly productive, small r-strategists.

In addition to the three colonizing mechanisms discussed above, relocated benthic fauna present within the subtidal dredged material may survive transportation (Jones, 1986; Harvey, *et al.*, 1998; Boyd, 1999) and assist recovery by facilitating the re-colonization of dredging disposal areas from within (DEFRA, 2000). Few studies have considered the condition and fate of animals within relocated dredged material, Jones (1986) investigated the survival of both transport and burial. For example, numerically dominant species such as *T. stroemi* survived both transport and burial and recovered quickly although species richness was reduced at the disposal site.

6.4 Sediment characteristics and biological response to changes in abiotic variables

The present macro-faunal settlement study examined the sedimentary characteristics of the manipulated sediment treatments and benthic invertebrate recovery. In general, some mollusc species were negatively correlated to an increase in the sediment water content. For example, *M. balthica* colonization of the fluid mud treatments (via settlement) was negatively affected when deposited at the high- or mid-shore areas and *H. ulvae* colonization was negatively affected when fluid mud treatments are deposited at the upper- and high-shore areas. Also, juvenile Tellinacea colonization was negatively affected by an increase in sediment water content when treatments were deposited at the high-shore. However, *T. benedii* was the only species to exhibit a sediment-associated pattern at the high-shore and its density was positively correlated to an increase in sediment water content; the mean densities of *T. benedii* were greater in the fluid mud treatments than in the actual mudflat control cores. Other studies have compared the sediment characteristics and benthic invertebrate communities of dredged material constructed intertidal mudflats to natural mudflats, in the UK (EA, 1998), in the Venice lagoon (Cecconi, 1997) and in Jonesport, Maine (USA) (Ray, 2000), thus providing details of macro-invertebrate recovery mechanisms. Harvey, *et al.*, (1998) postulated that the rate of recovery of a vegetative cover and infaunal community of an intertidal recharge site will depend on environmental variables such as the rate and frequency of dredged material deposition and the degree of natural recruitment.

To prevent or reduce the direct inhibition of a benthic community during a beneficial use scheme, several abiotic factors should be addressed: the depth, the composition and fluidity of the dredged material to be deposited. If the dredged material were too fluid to permit migration through it, colonization would be inhibited until sufficient consolidation had occurred. A number of macro-invertebrate species poorly colonized the fluid mud treatments of the current settlement studies including species such as *M. balthica*, *P. elegans*, *S. shrubsolii*, *P. litoralis* and Enchytraied species (Chapters 4 and 5). Additionally, the timing of a sediment recharge operation and the frequency of deposition are important, in order to avoid placement close to the main recruitment phase during the spring-summer period (Elliott, *et al.*, 2000). Furthermore, the ability of the dominant species at the recharge site to tolerate and survive burial must be considered (Elliott, *et al.*, 2000).

The presence of other benthic invertebrate groups in the created fluid mud sediment microcosms of this study were not significantly correlated with any sedimentary characteristics such as the percentage silt/clay or organic carbon content. It is postulated that macro-faunal recovery could occur following the release of organic matter and subsequent supply of nutrients (Moy and Levin, 1991; Harvey, *et al.*, 1998). Each species will respond differently, for example, the slow colonization of the gastropod *H. ulvae* in a fine-grained substratum was linked to a low organic content (Evans, *et al.*, 1998). After manipulating sediment characteristics such as the organic content and particle size of deposited material in a mudflat microcosm experiment, Bolam (2003) emphasized that the response of mudflat fauna should be considered during the licensing process (see Appendices). Bolam's (2003) study showed a poor macro-faunal recovery in a 6 cm and 16 cm sediment overburden such as the polychaetes *Tharyx* "A" (Unicomarine) and *S. shrubsolii*. The oligochaete *T. benedii* showed some vertical migration into a 6 cm sediment overburden when the treatment organic content was low, whilst *H. ulvae* recovered quickly from a sediment deposition of 16 cm. Additionally, he noted that the vertical migration ability of macro-fauna was not restricted by an increase of sediment sand content from 16 % to 38 % but was affected by an increase of sediment organic content from 0.8 % to 3.4 %. However, Ford, *et al.*, (2001) reported organic matter had a two-way effect on the colonization ability of the corophiid amphipod *Paracorophium excavatum* - the findings from laboratory and field manipulation experiments revealed an increase of colonizing corophiid juveniles when organic loads were low and a decrease in corophiid colonization when organic loads increase.

6.5 Implications for fine-grained beneficial use schemes

The present study provides valuable information to managers wishing to minimize the possible harmful effects upon the benthic invertebrate community of an area of mudflat to be nourished. The results are particularly valuable for the implementation of thin-layer deposition recharge schemes where maintenance dredged material is deposited in relatively small amounts – similar to those used in the present study. This study used common benthic invertebrates of a temperate mudflat area to be recharged, the data presented here will provide information on the amounts and frequency of sediment deposition that may be used during a recharge scheme, to reduce the potential detrimental effects upon the benthic community. These findings increase our knowledge of the rate of recovery of buried indigenous faunal patches and could be useful in terms of macro-invertebrate survival rates and annual changes in abundance during beneficial use schemes. The present studies have shown that certain species are able to vertically migrate into depositions of up to 20 cm when placed as 2 cm thin veneers, deposited every 4 days (Chapter 2). Miller, *et al.*, (2002) suggested that a slow rate of deposition of 1 cm per deposition occasion to a total burial depth of less than 10 cm. However, Bolam (2003) suggested depositing dredged material as thin veneers in the form of several centimetres to prevent or minimise the detrimental impact/affects of burial on the mudflat fauna.

During the licensing process certain sedimentary characteristics such as chemical contaminants, particle size and organic content of dredged material are analysed at source, this process can determine the suitability of the dredged material for a beneficial use scheme at an early stage. Careful consideration of a number of biological, chemical and physical factors should be made when comparing the small-scale experimental results with those of the larger-scale beneficial use schemes, as the migratory behaviour of mudflat fauna may be affected differently and could be scale-dependent. Other considerations include the degree of exposure to wind-wave action, the resultant tidal elevation and the nature of the colonizing biota (Widdows, *et al.*, 2006). Similarly, differences may exist between beneficial use schemes. For example, species assemblage composition, the hydrodynamics and nature of the receiving area, the amount and frequency of dredged material deposition (Bolam, *et al.*, 2006) and may yield different rates and outcomes of macro-faunal recovery.

The temperate mudflat fauna are a source of prey for higher organisms such as wading birds, also migratory birds need to refuel and forage for long periods, especially during cold winters (Evans, *et al.*, 1998). Additionally, the prey species are important in terms of supporting commercially exploited fish and crustacea and bird feeding (McLusky and Elliott, 2004). Therefore, any detrimental impact on the estuarine benthic invertebrate community following sediment recharge will have an immediate effect on the carrying capacity of the mudflat and on migrating fish and birds, i.e. a secondary impact on bird populations using recharged mudflats. If a change in the prey species of sediment microcosms positioned in the mudflat occurs when compared to the natural mudflat, subsequent changes to biological parameters such as the density of prey species will take place, additionally parameters such as the size and biomass spectrum may be affected, for example, the upper-shore mud treatment total individuals biomass was similar to the mudflat control biomass but the high- and mid-shore biomasses remained dissimilar (Chapter 4). This information may be useful when considering the possible effects of a newly recharged area of mudflat. Consequently, the suitability of an area of mudflat for certain bird species with more specialised feeding preferences may be affected, for example, the feeding efficacy via visual clues may be affected by smothering of prey (Elliott, *et al.*, 2000). Hence the necessity to monitor fish and wading bird utilization of an area of mudflat destined for recharge, both pre- and post-dredged material deposition. Additionally, changes to the topography and tidal regime following sediment recharge will affect the feeding regime, for example, an increase in mudflat height of an area will increase exposure and bird feeding time. However, an increase in mudflat exposure time may reduce the production or carry capacity of an area and its value as a feeding resource until the community structure has recovered (Beukema, *et al.*, 1999). Therefore, the functionality of an enhanced or created habitat may need to be maintained (Moy and Levin, 1991; Levin, *et al.*, 1996; Minello, 2000). However, if sea level rise occurs then the tidal height will keep pace.

This study had limited spatial and temporal coverage because of affordable time. Clearly, given the documented variation in soft-sediment communities over a range of scales of space and time these results need to be viewed with some caution. However, the results presented here from field and laboratory experiments clearly demonstrate that the most important factors to consider during a burial study are the depth of overburden deposited, the nature of the overburden, the period of burial and the time of year. These results can be used and placed towards the beneficial end of the conceptual model scale of ecological consequences of dredged material disposal in the coastal environment provided by Bolam, *et al.*, (2006) (Figure 6.5). Widdows, *et al.*, (2006) noted the timing of dredged material deposition is critical in terms of reducing sediment erosion with autumn and winter deposition likely to be the greatest. Intertidal sediment erosion is reduced during the spring-summer and dredged material depositions are more likely to become stabilized by physical and biological processes. Also, uncontaminated fine-grained dredged material can be placed as a mound on the intertidal and a new mudflat may be created following stabilisation with seagrasses (PIANC, 1992) by trapping suspended sediments (DEFRA, 2000) and thus reduce wave energy and erosion potential. Based on the findings of the present studies and other studies related to the beneficial use of dredged material in the UK, it is recommended that the trickle recharge of an area of mudflat take place a short time prior to the spring period. However, the effects of the spring equinox when the tidal regime is at its greatest should be considered at the recharge site and a further trickle recharge may be necessary. Such a strategy would provide sufficient time for the biological and physical stabilization of the recharge material over the spring-summer.

Adverse **Beneficial**

Effect on ecosystem integrity in response to dredged material disposal

- Ecological effects of disposal may be viewed along a continuum
- All disposal options (including "beneficial use") may be lie anywhere along this effects continuum
- All options must ultimately be treated on a case-by-case basis*
- Management decisions must balance operational and ecological consequences

* Effects primarily depend upon the site specific factors such as (i) the amount and (ii) frequency of disposal, (iii) the quality of dredged material and (iv) the nature of the receiving environment

Figure 6.5: Conceptual model of the ecological consequences of dredged material disposal in the coastal environment (From: Bolam, *et al.*, 2006).

6.6 Conclusions

The short-term laboratory based experiment and all experimental field studies within the project were undertaken to assess the alternative beneficial use of uncontaminated maintenance dredged material in mudflat recharge schemes. Consequently, the study has provided the non-ecologist and licence officers new information for new beneficial use schemes. The experimental studies have been used to refine/develop conceptual model diagrams. The main conclusions are:

1. Macro-faunal recovery does take place when a single low frequency mud deposition occurs during the winter period and resident macro-fauna from areas adjacent to the disposal site re-colonize the newly deposited material through active vertical or horizontal immigration. However, the timing and depth of dredged material deposition should be considered and the deposition of material around important faunistic recruitment periods taking place around the spring period should be avoided. (See 6.5 for recommendations);
2. A further important mechanism of re-colonization of simulated fine-grained dredged material was the recruitment of juvenile and adult macro-fauna via settlement from the water column. The sampling of macro-faunal communities over a 17-week period (Chapter 4) followed by a 10-week period (Chapter 5) enabled the evaluation of spatial and temporal changes in colonist communities. The re-colonization of manipulated fluid mud treatments (Chapters 4 and 5) demonstrated a rich and diverse macro-faunal assemblage was present within 10-weeks at the high- and upper-shore areas;
3. This study indicates that estuarine benthic macro-fauna have a high ability to re-colonize newly deposited sediments through three re-colonization mechanisms: vertical migration, below surface lateral migration and macro-faunal settlement from the water column (Figure 6.6). Some species are more mobile such as *H. diversicolor* and *M. balthica* so can migrate through a sediment overburden and *T. benedii* successfully colonized a high-water mud treatment. Other species are more sensitive to sediment treatment type, more specifically particle size. For example, nematodes experienced more mortalities when a sandy deposition was placed than a mud treatment. In general, the surface layers of a sediment overburden had the greatest species abundances suggesting each indicator species was capable of maintaining a position within the upper layers of the sediment profile;
4. The macro-faunal recovery (such as total individuals, species richness, diversity and evenness) of a recharge site or experimental microcosms will be dependent on the spatial variability of the adjacent mudflat faunal communities. For example, if the recharge site is surrounded by patches of low biological richness and abundances, the re-colonization of newly deposited material may be delayed/slow due to a poor supply of immigrants from adjacent mudflat areas. Furthermore, the nature of a mudflat faunal community, in particular the species present within the community, will have different migration abilities and sediment preferences and may effect the recovery of a newly placed overburden (either detrimentally by delaying the recovery process or by speeding up recovery if, for example, many opportunistic species are present). In this study,

certain mollusc species such as *M. balthica*, *H. ulvae* and juvenile Tellinacea were negatively correlated to an increase in sediment water content at the high-shore;

5. Changes to the topography and tidal regime following sediment recharge will affect the feeding regime of migrating fish and wading birds. For example, an increase in mudflat height of an area will increase exposure and bird feeding time but may reduce the production or carrying capacity of an area and its value as a feeding resource until the invertebrate community structure has recovered. Hence the necessity to monitor the amount of fish and wading bird utilization of an area of mudflat destined for recharge, both pre- and post-dredged material deposition;
6. To conclude it appears possible that specific active mobile mudflat fauna are capable of (a) vertical migration with increasing depths of sediment overburden and (b) immigration from adjacent areas and (c) settlement from the water column. These results indicate that a careful consideration of (a) the nature of the receiving area, (b) the tidal height chosen for sediment recharge, (c) the nature of the benthic community of the pre-recharge area and (d) the sediment water content of the fine-grained dredged material for deposition should be made during the licensing process of beneficial use schemes.

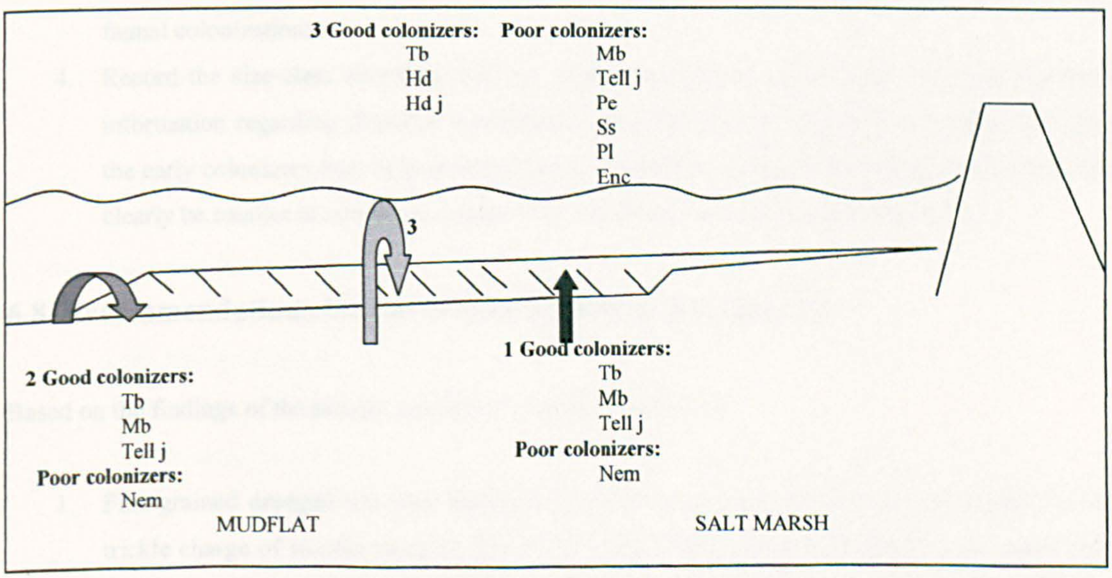

Figure 6.6: Macro-faunal re-colonization potential of simulated dredged material. Note: This is a summary of the field manipulation experiments only.

Key

1 = Vertical migration
2 = Horizontal migration
3 = Settlement from water column

Species key:

M. balthica (Mb)	*H. diversicolor* (Hd)	*S. shrubsolii* (Ss)	Enchytraeidae (Enc)
Tellinacea j (Tell j)	*H. diversicolor* j (Hdj)	*T. benedii* (Tb)	Nematoda (Nem)
M. aestuarina (Ma)	*P. elegans* (Pe)	*P. litoralis* (Pl)	

6.7 Recommendations for further study

The recommendations for further study are:

1. Record the size-class frequency or volume (using geometric shapes) of bivalve molluscs and polychaetes within each sediment veneer (by measuring shell length or peristomium width and relating size to burrowing ability or particle size. Check the sediment chemistry of deposited beneficial use sediment on each sampling occasion such as redox values, organic content, oxygen levels and changes in sediment sulphide content. Also, consider more physical characteristics of the deposited sediment such as the bulk density and shear strength;
2. Monitor fish, nekton and bird utilization of the beneficial use schemes and adjacent control mudflat communities. For example, to monitor the fish utilization of an area of mudflat deploy Fyke nets and bottle traps to determine what species of fish are utilizing the recharge scheme. Secondly, undertake regular bird surveys of the recharge scheme to monitor which bird species and what numbers are using the recharge area;
3. Use more replicates (up to five) to provide a better understanding of the distribution of macro-faunal colonization;
4. Record the size-class distribution of the colonizing mudflat species, this may provide further information regarding dispersal mechanisms used such as the settlement of post-larvae stages, the early colonizers may be post-larval recruits from the planktonic recruitment stage and would clearly be smaller in size when compared to an actively migrating adult individual.

6.8 Recommendations for use of information in management

Based on the findings of the present research it is recommended that:

1. Fine-grained dredged material deposition as a single amount of up to 20 cm depth or a slow trickle charge of smaller amounts (of 2 cm) to allow the sediment to regain its structure and to take place prior to the spring period, thereby allowing sufficient time for the re-colonization process to begin via the active immigration of certain adult macro-faunal species from adjacent areas and from below the recharge material and via settlement from above. If an area is recharged during the autumn and winter months, an increase in sediment erosion rates may occur and the recharge material may become eroded as the recharge sediment may not become physically and biologically stable until the spring-summer. Therefore, if an area is recharged during the winter, a second sediment recharge event may be necessary and should occur prior to the spring period, although sediment deposition should not occur around the highest astronomical tides, thus allowing the bio-stabilization of the deposition. These recommendations would be site dependent and local sediment erosion processes should be considered and only one recharge event may be necessary such as trickle charging slowly over a month or as a single larger deposition;

2. A number of beneficial use schemes have been monitored for macro-faunal and abiotic recovery from the initial period of dredged material deposition to the present and further monitoring of such schemes should continue for the foreseeable future to determine the precise recovery mechanisms and to detect long-term biotic and/or abiotic changes.

6.9 Critique and limitations of studies

- The experimental design used for the field studies conducted in Chapters 4 and 5 could have been merged to monitor macro-faunal colonization over a continual study period of up to 18 months and samples could have been taken bi-weekly throughout the first spring/summer period and monthly or bi-monthly over the winter period before a second intensive spring/summer sampling regime, this longer monitoring regime would have been more similar to the early recovery time scale of a beneficial use scheme;
- Within the statistical analyses of the experimental data a type I or II error may have occurred when deciding the significance of a null hypothesis and in some instances a null hypothesis may have been rejected or accepted when the opposite may have been true. However, a lower P value ($P < 0.01$) could have been used to reduce the likelihood of type I or II error. Also, in some cases the Mauchley's test of spherecity was violated when using ANOVA repeated measures (these results were added to the appendices and not considered as valid);
- The size class distribution of the colonizing mudflat species were not recorded during these studies due to affordable time;
- The particle size analysis and organic carbon content of the experimental sediment treatments used in Chapter 2 were not taken in this study due to time constraints. As a consequence no statistical investigations were undertaken relating the biota to the sedimentary characteristics of the experimental sediment treatments;
- The defaunation method of freeze-thawing used throughout these studies can alter sediment structure and thus change the sediment composition.

The main limitations experienced during the experimental investigations undertaken are listed below:

- A greater number of replicates such as an increase to five replicates may have increased the ability to detect subtle changes or increased the reliability of the data. However, due to the logistical constraints encountered within the field and the laboratory, an increase of replicates was considered unfeasible;
- Due to the large amounts of experimental material to be processed, all samples were fixed prior to sorting (with the exception of the aquarium based experiment (Chapter 2)) therefore macro-faunal mortality within each sediment increment was not considered in the subsequent Chapters 3 to 5. It would have been advantageous to check the mortality of each animal, after migration into the sediment profile;

- Problems with 'streaming' and faunal contamination between the layers may have occurred when using the sediment corer plunger, although this is thought to be minimal due to the design of the plunger;
- During some burial studies such as Sharpless (2000), the sediment treatment deposition was added to the experimental microcosm over a period of one hour. In the present studies, this was not possible. Therefore, the simulated dredged material was added instantly to the surface of the microcosm mudflat core;
- During the field studies adverse weather conditions occurred on several sampling occasions (throughout the seasons) and difficulties were experienced that prevented samples to be taken, therefore sampling dates had to be postponed and re-assessed. Consequently, not all replicates were taken during these times and may have been taken over 2 days or postponed.

Overall the main aim of this research was to provide experimental evidence concerning the impact of burial following the deposition of simulated dredged material on a temperate intertidal mudflat community. Additionally, the logistics of dredged material deposition at different tidal heights was investigated. This was achieved by examining the responses of key mudflat macro-fauna to burial by manipulated sediment treatments deposited at the upper-, high- and mid-shore areas of an estuarine intertidal mudflat and determining the macro-faunal re-colonization potential.

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