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Modification of benthic ecosystems by offshore wind farms: implications for natural capital and ecosystem services

School of Water, Energy and Environment

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Abstract

Due to concerns about climate change and energy security there has been considerable growth in the installed capacity of offshore wind energy worldwide over the last two decades. Owing to engineering constraints offshore wind turbines have generally been installed in areas characterised by soft sediments. Offshore wind farms introduce hard substrate and intertidal zones into these areas and have the capacity to alter natural capital, including biodiversity, in benthic ecosystems. Changes in benthic habitats may result in changes to the ecosystem services (goods and benefits people receive from nature) provided by natural functions and processes. Thus, continued expansion in offshore wind energy has the potential to affect natural capital and the associated delivery of ecosystem services.

Differences in benthic community composition between manufactured structures, natural rock reefs and soft sediments in the southern North Sea were found to be significant ($P < 0.05$) through permutational analysis of variance (PERMANOVA). However, evidence suggests that ecosystem functioning remained similar between natural substrata and offshore energy structures. Based on a Monte-Carlo analysis there were no significant differences in trait expression between the habitat types for the most dominant taxa. There were significant differences in feeding mode, longevity and larval duration amongst less common taxa ($P < 0.05$), however their effect is likely to be muted.

An assessment of natural capital demonstrated that offshore wind farms present risks and benefits to natural capital and the associated ecosystem services. The Thanet offshore wind farm was used as a case study. Overall, the natural capital increased following the installation of the wind farm. Targeted investment to support natural capital within offshore wind farms can produce functional ecosystems that not only produce low carbon energy but also augment ecosystem services; a number of which can have economic benefits. The findings have implications for the design, operation, maintenance and end of life treatment of offshore windfarms.

Keywords: Biofouling, Colonisation, Ecosystem Function, Monitoring, Renewable Energy

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Table of contents

List of figures

List of tables

List of figures for appendices

List of tables for appendices

List of abbreviations

AWI	Alfred Wegener Institute
BAP	Biodiversity Action Plan
CFD	Computational Fluid Dynamics
CIA	Co-Inertia Analysis
CMACS	Centre for Marine and Coastal Studies Ltd
DDT	Dichlorodiphenyltrichloroethane
EIA	Environmental Impact Assessment
EMF	Electromagnetic Fields
FPCA	Fuzzy Principal Components Analysis
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
NCA	Natural Capital Assessment
NCC	Natural Capital Committee
NMS	Nonmetric Multidimensional Scaling
MBES	Multibeam Echosounder Systems
MES	Marine Ecological Surveys Ltd
OWF	Offshore Wind Farm
PAH	Polycyclic Aromatic Hydrocarbons
PCB	Polychlorinated Biphenyls
PCA	Principal Components Analysis
PERMANOVA	Permutational Analysis of Variance
SSS	Side-Scan Sonar
SST	Sea Surface Temperatures
TDS	Thanet Development Site
WUR	Wageningen University and Research

Chapter 1: Introduction

1.1 Background

The installation of offshore energy structures began in the mid-nineteenth century; in 1947 Kerr-McGee oil drilled the first productive offshore well in shallow water (approximately 5.5 m) in the Gulf of Mexico, 10.5 miles off the coast of Louisiana, USA (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2010). Activity in the Gulf of Mexico rapidly expanded, fuelled by an import embargo imposed by the US government from 1959 to 1971 (Pinder, 2001). Petrochemical exploitation in the southern North Sea soon followed, with production beginning in the 1967 (Kerckhof et al., 2011; Pinder, 2001). Since those pioneer installations, fleets of offshore oil and gas production and support platforms have been installed worldwide (Sadeghi, 2007). These include floating structures, such as Jack-up platforms, as well as submersible and semi-submersible platforms, and fixed platforms such as those constructed on steel jacket or concrete gravity foundations (figure 1) (Sabri et al., 2014).

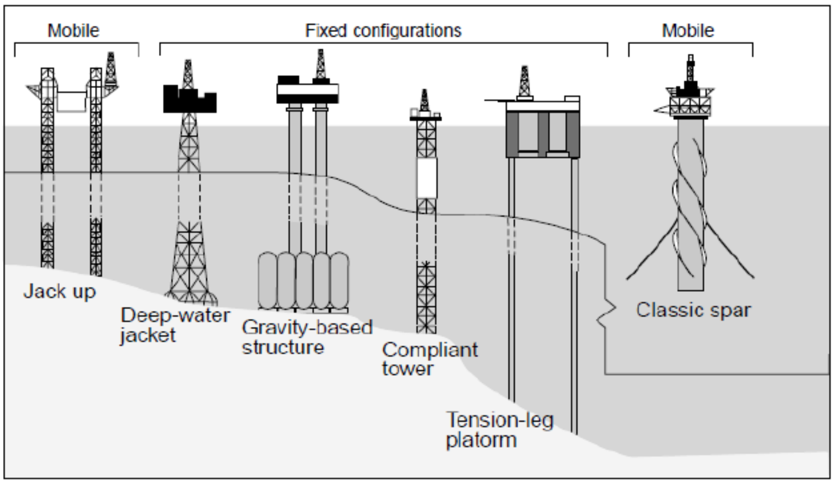


Figure 1 Types of offshore platforms (Sabri et al, 2014)

An increased awareness of the effects of rising CO_2 emissions, largely as a result of fossil fuel exploitation, and concerns over energy security have led to growing investment in offshore renewable energy (Mangi, 2013; Szulecki et al., 2016; Voormolen et al., 2016). Human induced climate change presents environmental risks that are numerous and complex. Higher sea surface temperatures (SST), sea levels, storm frequency and wind velocity have occurred due to rises in atmospheric CO_2, along with changes in ocean circulation, and nutrient loads (Harley et al., 2006). Further, as atmospheric CO_2 levels increase so does the level of dissolved CO_2 in sea water, which forms carbonic acid (H_2CO_3), reducing the pH (Brierley and Kingsford, 2009; Harley et al., 2006; IPCC, 2014, 2007; Rahmstorf, 2007).

Climate change is a major contributor to biodiversity loss (Dziba et al., 2019; Masson-Delmotte et al., 2018). Present rates of species extinctions are tens to hundreds of times greater than the average rate over the past 10 million years, and are accelerating (Dziba et al., 2019). Declines in biodiversity are set to worsen in response to rapid human population growth and unsustainable production and consumption associated with technological development (Dziba et al., 2019). The human population is expected to reach 10 billion by 2100 (Guerry et al., 2015).

Given the evidence for risks from climate change, and the alarming rate of biodiversity loss (Ceballos et al., 2015; Dziba et al., 2019) there is little doubt we are facing an ecological crisis. Concerns around climate change and sustainability have been heightened following the release of the special report by the Intergovernmental Panel on Climate Change (IPCC) (Masson-Delmotte et al., 2018). This report states that human activities have caused $1^{o}C$ of warming above pre-industrial levels, and without major and immediate intervention temperatures are likely to rise to $1.5^{o}C$ between 2030 and 2052 (Masson-Delmotte et al., 2018). It is considered that limiting global warming to $<1.5^{o}C$ would mitigate risks associated with climate change, enabling greater opportunities for humans and ecological systems to adapt (Masson-Delmotte et al., 2018).

Global energy demand has generally increased with population growth, urbanisation and modernisation (Asif and Muneer, 2007). Renewable energy is considered necessary to meet global energy demands and CO_2 emission targets, and preventing further global warming (Choi, 2018; European Commission, 2018a, 2018b; Masson-Delmotte et al., 2018). Over the last two decades, offshore wind energy has seen considerable investment, particularly in Europe where cumulative installed capacity rose from 0.8 GW in 2006 to 12.6 GW in 2016 (Bilgili et al., 2011; Corbetta and Miloradovic, 2016; Walsh, 2018). Given the future expansion expected, offshore wind may contribute more than around 140 GW, approximately 10% of Europe’s energy demand, by 2030 (Langhamer, 2012; Zervos et al., 2009). However, Masson-Delmotte et al (2018) estimated that to constrain global warming to 1.5°C, with limited or no overshoot, renewable energy should supply 70-85% (interquartile range) of electricity in 2050.

Whilst it is generally considered that by reducing CO_2 emissions offshore wind farms (OWFs) benefit the environment, hard substrate introduced by turbines are rapidly colonised by epibenthic species with sessile life stages (Kerckhof et al., 2009; Langhamer, 2012). As a result, an OWF has the potential to alter benthic communities considerably. In altering biodiversity and introducing new habitat, OWFs can change natural capital. The term natural capital refers to stocks of natural assets that generate ecosystem services (Costanza and Daly, 1992; Hinterberger et al., 1997; Natural Capital Committee, 2014), goods and benefits humans derive from nature (Carpenter and Turner, 2000; Costanza et al., 2014a; Liquete et al., 2013; Mace et al., 2012). Natural capital includes biotic (e.g. biodiversity and biomass) and abiotic (e.g. water and sediments) components of an ecosystem (Costanza et al., 2017).

Although evidence is not definitive, there are concerns that with biodiversity loss there will subsequently be loss in ecosystem services (Cardinale et al., 2012). Ecosystem services are products of ecosystem processes and functions (Sandifer et al., 2015), and traits that predispose species to extinction often drive ecosystem processes (Suding et al., 2008; Wardle et al., 2011). Natural capital and ecosystem services have received considerable attention in terrestrial systems (Naidoo et al., 2008), but have received less attention in marine systems. Oceans contribute a wide variety of ecosystem services but are large and taxonomically complex, so scaling up from local to global scales is particularly challenging (Hendriks et al., 2006). In recent years there have been several studies in to the effects of OWFs on the delivery of ecosystem services (Busch et al., 2011; Hattam et al., 2015; Mangi, 2013; Wilding et al., 2017). Yet linkages have not been made between to the potential for biodiversity change to alter ecosystem functioning and subsequent effects on ecosystem services.

As the offshore wind industry continues to expand there is a need to understand the effects of OWFs on marine natural capital and associated ecosystem services, which maybe positive as well as negative. Under current regulations an environmental impact assessment (EIA) is required prior to installation of an OWF. An EIA is a legislative tool intended to gather information about the environmental effects of a development for decision-making in order to mitigate anthropogenic impacts (Kominkova, 2008). Yet there has been criticism that EIAs emphasise negative impacts and are ineffective at evaluating positive and non-local benefits (Hooper et al., 2017b; Smart et al., 2014). An alternative approach would be one that incorporates changes in natural capital and assesses the trade-offs between potential impacts and benefits, in relation to ecosystem functioning and associated services.

1.2 Benthic colonisation of structures

1.2.1 Dispersal and settlement

Epibenthic organisms are transported from one location to another through a mechanism known as dispersal. This is a complex process that takes place via a combination of physical and biological processes (Cowen and Sponaugle, 2009).

Towards the end of the 20th century it was widely assumed that populations were open and larval exchange was a passive process that occurred over hundreds to thousands of kilometres (Caley et al., 1996; Cowen and Sponaugle, 2009; Stobutzki, 2001). Whilst passive transport does occur over long distances (>km), as advection exceeds larval swimming capacity (Archambault and Bourget, 1999), there is mounting evidence that larval retention occurs frequently in the natural habitat (Almany et al., 2007; Hellberg et al., 2002; Levin, 2006). Larvae may be retained by interactions with local geographical features, or recirculating currents and eddies. Thus, many larvae transported offshore may be recirculated back to the adult environment (Strathmann et al., 2002).

Nevertheless, the development and persistence of epibenthic communities on offshore structures does indicate a certain level of offshore transport, although the exact measure relative to the size of the larval pool is unknown. Given that the offshore environment typically lacks hard substrate colonisation of artificial structures is most likely opportunistic. However, whether in the absence of such substrate larvae would ordinarily be recirculated back towards the natural adult environment or die off is not fully understood. Dispersal potential is complex and is intimately linked to larval growth rates and ability to locate suitable substrate. Whilst larval swimming ability is limited it is important in fine scale habitat selection and vertical migration. It has been shown that small deviations in vertical distribution can result in the transportation of larvae to entirely different geographical locations (Hare et al., 2005; Hinckley et al., 1996; Vikebø et al., 2005). Thus, larval swimming may be an important determinant of dispersal as well as settlement in the adult habitat.

As larvae develop and grow in the planktonic environment, they eventually become competent to settle, enabling a shift from one environment to another. Settlement may be a passive process; transport to surfaces is by hydrodynamics alone (Prendergast, 2010). Or it may be an active process, where larvae respond to cues, which signify the surface is favourable for survival and reproduction, and can trigger adhesive release or a change in behaviour to facilitate settlement (Fusetani, 2004; Prendergast, 2010). For example, larvae of the pacific oyster, *Crassostrea gigas*, ‘dive-bombs’ when in interaction range (one or two body lengths) of the surface (Prendergast, 2010). *Cliona celata* and *Microciona prolifera* have been found to swim towards the water surface, where they may increase their likelihood of encountering an intertidal substrate (Prendergast, 2010).

Those that can settle indiscriminately are likely to colonise surfaces soon after they are competent, whereas those that rely on environmental cues may settle much later (Krug, 2001; Toonen and Pawlik, 1994). Variation in settlement behaviour can lead to variation in dispersal potential (Marshall and Keough, 2003). Although, it has been argued that as larvae age they become less discriminatory in their choice of substrate (Gibson, 1995; Knight-Jones, 1953, 1951; Wilson, 1953). This is supported by the finding that in non-feeding larvae, where settlement cues are absent, those that are smaller, with lower energy reserves settle sooner than those that are larger with greater energy reserves

(Marshall and Keough, 2003). Failure to encounter suitable substrate would result in mortality (Prendergast, 2010).

Behavioural responses, such as searching and testing settlement spots following contact with a surface, may influence spatial patterns of settlement and survival (Porri et al., 2006). On spatial scales of µm to cm, substratum topography or quality can affect survival after settlement of barnacles and bryozoans (Walters and Wethey, 1996). Thus, colonisation of hard surfaces can be viewed as a combination of biological and behavioural responses by macro and microorganisms to chemical and physical stimuli that is expected to vary spatially and through time.

In creating new habitat, turbine foundations provide opportunities for food and shelter, thereby raising biodiversity. Empirical evidence indicates increased species richness raises ecosystem functionality (Lefcheck et al., 2015). Key processes are supported by biodiversity, which deliver multiple functions that affect the provision of ecosystem services (Mace et al., 2012; Reiss et al., 2009; Snelgrove et al., 2014). Thus, in raising biodiversity, OWFs may alter the delivery of ecosystem services.

1.2.2 Biofouling; the effects of colonisation on offshore structures

Unwanted colonisation of offshore structures by marine organisms is frequently referred to as biofouling, and is a major consideration for marine energy engineers; marine colonisation has been shown to increase the cross-sectional area for all subsurface offshore structures as well as increase surface roughness (Fevåg, 2012; Jusoh and Wolfram, 1996; Shi et al., 2012a; Theophanatos and Wolfram, 1989), which in turn gives rise to changes in drag and inertia coefficients (Shi et al., 2012a). Thus, settlement on a structure can greatly increase hydrodynamic loading (Yan and Yan, 2003). Indeed, Shi et al (2012a) noted that the marine colonisation effect is considered important for load assessments, especially fatigue behaviour of jacket structures. A layer of growth 15 mm thick may increase loading by 17.5%, causing 62.3% increase in fatigue damage and a 38% decrease in fatigue life (Heaf, 1979), which is the number of loading (stress) cycles a structure can sustain before failure (Xin, 2013). As discussed, settlement dynamics of marine organisms on offshore wind turbines may vary greatly based on location, structural characteristics and season. For example, studies have demonstrated that biodiversity and abundance are generally greater in summer (Kerckhof et al., 2010, 2009; Reiss and Kröncke, 2004). It can be assumed therefore that corresponding stresses and inertia will fluctuate in a similar manner. However, few studies have investigated the effects of marine colonisation on structural loading, and experimental evidence is almost absent from the literature. So, it is difficult to predict the long-term implications for wind turbines.

Figure 2 Thanet offshore wind farm 5 MW turbine (left) standing on a monopile foundation (image modified from Werdigier, 2010). Beatrice offshore wind farm 7 MW turbine (centre) standing on a jacket offshore wind farm (image modified from 4C Offshore, 2019). Wind float 2 MW test turbine (right) standing on a floating barge structure (image modified from Weyndling, 2019).

As the industry matures, wind farm developments are expected to utilise larger turbines and move further offshore where wind is typically stronger and more consistent (Bilgili et al., 2011). Figure 2 shows turbines constructed on a monopile, a jacket foundation and a floating barge structure. In the UK sector of the North Sea, The Crown Estate has leased different areas for offshore wind developments, with leasing rounds being released at different times (Toke, 2011). Most operational wind turbines to date have been built on monopile foundations in shallow coastal waters under leasing round 1 and 2 (Kolios et al., 2014). However round 3 projects, and potentially round 4 (The Crown

Estate, 2019), are expected to occupy waters of >30 m depth (Doherty, 2011). Due to high flexibility in greater depths monopiles are limited to waters of around 25-30 m depth.

The wider base of jacket foundations (figure 2) are more suited to neutralising overturning forces and less reactive to wave resonance (Higgins and Foley, 2014; Lozano-Minguez et al., 2011; Musial and Ram, 2010). Jackets have commonly been used in the oil and gas sector, but in recent years have been used to support wind turbines in waters ranging in depth from 35 to 60 metres (Doherty, 2011). As such, jackets may become more common as wind turbines are installed in deeper waters. However, jackets are costlier than monopiles (Myhr et al., 2014). It is considered that at greater depths floating turbines may be the most economical structure (Jonkman, 2009; Musial et al., 2004). As such jackets may prove to be a transitional technology seeing less use as floating turbines become commercially available. Floating turbines (figure 2) offer clear advantages over fixed structures. They can be fully fabricated prior to deployment, then towed from shore and moored, using inexpensive anchor systems in waters up to 700 m (Wang et al., 2010). They can also be brought back to shore for maintenance and repair, rather than conducting expensive and high-risk operations at sea.

As with other submerged structures biofouling has been documented on wind turbines and a number of potential risks are recognised. For example, it has been suggested that biofouling may affect structural fatigue of wind turbines (Fevåg, 2012; Shi et al., 2012b). As such marine colonisation, could reduce their operational lifespan. Therefore, the potential influence of marine colonisation on fixed and floating turbines is a timely and novel topic, which could have significant implications for structural loading and inertia characteristics.

1.2.3 Possibilities for natural capital and ecosystem services from offshore wind farms

Ecosystem services have predominantly been interpreted in terms of economic value (Carpenter and Turner, 2000; Costanza et al., 1997), and there have been a number of attempts to quantify value of global ecosystems. Costanza et al (1997) conservatively estimated their value to be approximately $33 trillion per year (in 1995 $US), which was significantly larger than global gross domestic product (GDP) at the time. This estimate was based on the cost of replacing lost services artificially.

In recent years the concept has gained considerable attention. In 2005, the UN published its Millennium Ecosystems Assessment (MEA), a four-year study for policy makers (Costanza et al., 2014b). The MA was intended to assess the consequences of ecosystem change for human well-being and the scientific basis for action to enhance conservation and sustainable use of those systems (Millennium Ecosystem Assessment, 2005). Subsequently between 2007 and 2010, the UN published The Economics of Ecosystem and Biodiversity report (TEEB) and ecosystem services entered the consciousness of mainstream media and business (Costanza et al., 2014b).

Possibly the most important contribution of the ecosystem services concept is that it reframes the relationship between humans and the natural world, emphasising natural assets as critical components of wealth, well-being and sustainability (Costanza et al., 2014b). In doing so it provides a platform by which complex environmental issues can be presented in a way that is more tangible, allowing adequate weight to be given to ecosystem services in decision making processes (Costanza et al., 2014b).

However, whilst useful, economic value does not fully capture the value of an ecosystem (Liquete et al., 2013). Indeed, the general absence of property rights complicate economic valuation; as does the fact that many key services, although readily used by humanity, are not traded through markets (Lester et al., 2013). For example, marine organisms play a significant role in climate control through global materials cycling, such as CO_2 absorption and release (Sabine et al., 2004). Such services are not easily traceable or quantifiable. Other aspects may have high value in that they are essential to the functioning of the ecosystem, but they can only be expressed in biological terms (Gee and Burkhard, 2010; Heal, 2000). Coupled with high complexity between service links it becomes extremely challenging to provide accurate estimates in terms of economic value (Costanza et al., 2014b, 1997).

It is thought that the oceans contribute >60% of the total economic value of the biosphere, most of which is encompassed within the coastal zone (Costanza et al., 1997; Martínez et al., 2007). Yet attempts to quantify ecosystem services in the marine and coastal zone beyond fisheries and related industries have been lacking (Gee and Burkhard, 2010; Liquete et al., 2013; Turner et al., 2003). It is therefore not clear how wind farms may influence ecosystem services (Gee and Burkhard, 2010).

Few studies have addressed the possible effects of OWFs on the delivery of ecosystem services. Busch et al (2011) illustrate possible benefits to human wellbeing from significant wind farm development. They identified conflicting views between stakeholders and highlighted ambiguity within the ecosystem services concept. For example, the fishing community may regard OWFs as an obstacle to fishing, whereas conservationists argue OWFs could encourage the recovery of commercially exploited species (Ritterhoff et al., 2004). By preventing destructive fishing activities, OWFs may also facilitate the recovery of natural habitats, such as biogenic reefs. Moreover, it has also been noted that offshore wind farms have the potential for co-use in aquaculture of mussels and oysters (Busch et al., 2011; Michler-Cieluch et al., 2009). Therefore, there may be potential for OWFs to be designed in a way that promotes commercially important species. Thus, there is a potential for enhancing local natural capital that may have wider long-term benefits.

Goals towards sustainable development have been adopted by the United Nations (UN) to eliminate poverty, secure equitable livelihoods and safeguard the environment and natural resources (Sullivan et al., 2018; United Nations, 2015). To this end, natural capital should be preserved (Costanza and Daly, 1992; Markandya and Barbier, 1989; Yang and Hu, 2018). Natural capital may lend itself to being better quantified than ecosystem services as it consists of biota and physical components of ecosystems, which can be measured. Monitoring trends in natural capital before construction, and over the lifetime of an OWF, may allow patterns in ecosystem functioning and the delivery of ecosystem services to be estimated. This can encourage careful investment among developers towards supporting and enhancing natural capital, which has the potential to produce functional ecosystems that not only produce low carbon energy but also augment ecosystem services. Given the widely reported rapid decline in world-wide biodiversity, and risks to the environment and human-well-being from climate change, any added ecological value would further strengthen the case for expanding offshore wind.

1.3 Thesis aims and objectives

This thesis investigates how benthic habitats and biodiversity can be modified by offshore energy structures; analysis of what this means in terms of the contribution to local ecosystems from benthic communities was performed. The specific aim was to understand the implications of offshore wind energy developments to natural capital and the delivery of ecosystem services. To this end, the main objectives were:

1. To identify ecologically functional pathways through which OWFs may affect ecosystem services.
2. To quantify differences in biodiversity between communities on natural and artificial substrates and determine whether changes in biodiversity result in changes in functional diversity.
3. To assess natural capital and ecosystem services before and after the construction of an OWF.

This thesis was completed within the interdisciplinary renewable energy marine structures (REMS) doctoral training centre. Working alongside structural and mechanical engineers provided an opportunity to combine our efforts in cross disciplinary research. Such collaborations allowed for studies to be completed that were beyond the expertise of any one individual within the team. Therefore, the following secondary objectives, which have not been included in the body of this thesis, were addressed through interdisciplinary projects.

1. Determine the effects of epibenthic growth dynamics on offshore wind turbine fatigue.
2. Determine how colonisation by epibenthic communities' influences drag and hydrodynamic loading on a floating offshore wind turbine.

The interdisciplinary research undertaken, and their findings have been outlined below.

1.3.1 Field experiment

To meet the primary objectives, existing epibenthic datasets were collated and analysed through multivariate methods. However, early in the course of this research a field experiment was devised to explore the influence of spatial orientation on epibenthic colonisation and address the engineering objectives. For this experiment frames were designed to simulate surfaces found on offshore structures. They were constructed from S355 steel and coated in interzone 954 anti-corrosive paint (figure 3). The frames had 355 mm long and 20 mm diameter vertical and horizontal sections, and with diagonal sections at an angle of 49^{o} with a 437 mm length and 20 mm diameter. Thus, the frames provide surfaces at multiple orientations for colonisation.

Figure 3 S355 steel settlement frame with anti-corrosive coating of interzone 954.

The frames were suspended in vertical arrays (figure 4) between a subsurface buoy and a gravity anchor. A total of 5 mooring systems were deployed between roughly 2 and 13 km north west of the Westermost Rough wind farm (figure 5).

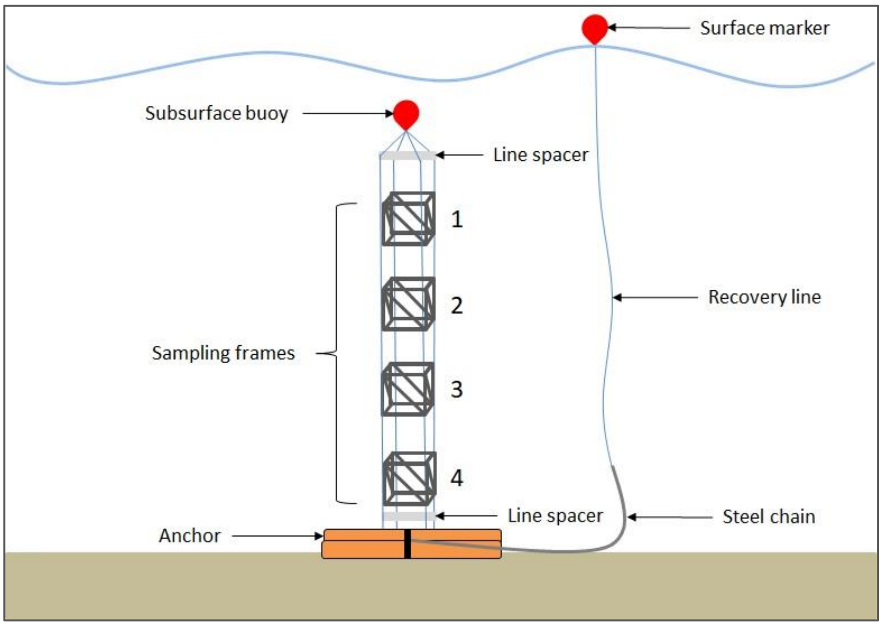


Figure 4 Temporary sampling array layout.

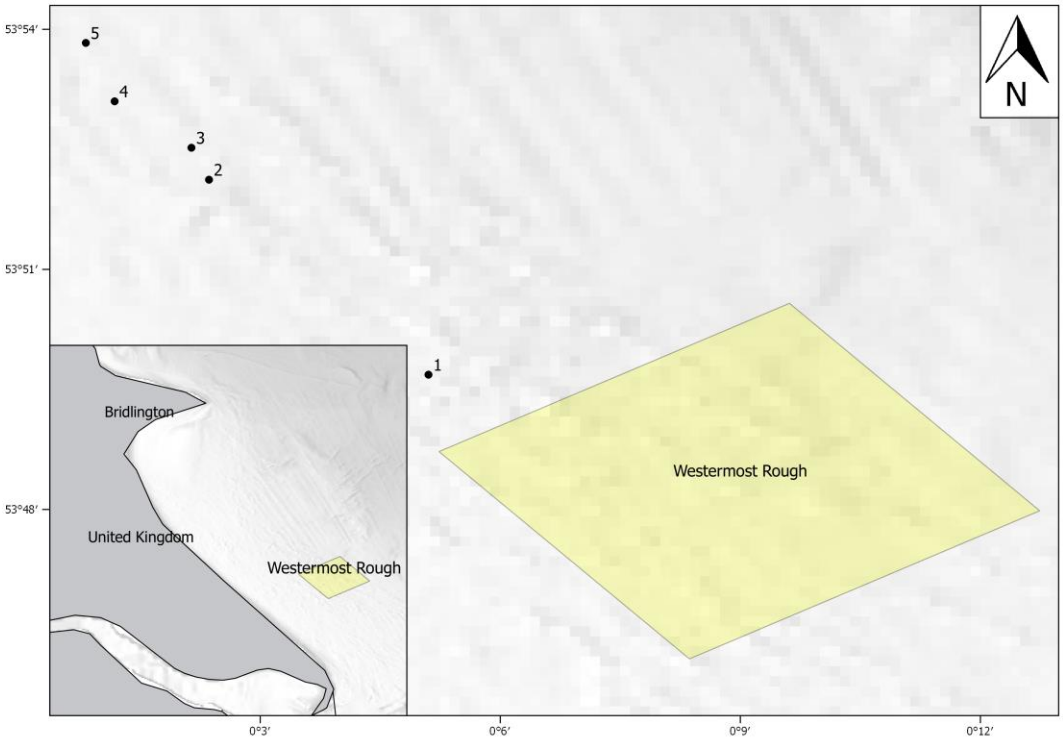


Figure 5 Map of array deployment (black points 1-5) relative to Westermost Rough OWF and Bridlington Harbour.

Subsurface buoys, which provided 90 kg of buoyancy force, were used to avoid most of the wave action on the surface. It was decided that polyform/foam filled buoys would be most suitable (figure 6). An air-filled buoy would suffer from compression effects caused by water pressure. Thus, the buoyancy force would change as the tide rises and falls, which could cause the buoy to become negatively buoyant and sink to the seabed at high tide.

Figure 6 Subsurface mooring buoy: Polyform Norway MB100 hard-shell foam-filled rod buoy (50cm diameter).

The gravity anchors were 250kg and were comprised of 2 aggregate filled webbed tubes (figure 7) weighted to 125 kg each. The mooring arrays were connected to a surface marker buoy with a recovery line that was connected to the anchor by a 10 m section of galvanised steel chain to prevent the recovery line from tangling with the array.

Figure 7 Aggregate filled tubes used to anchor the mooring systems.

Steel line spacers (figure 8) were installed above the anchor and beneath the buoy. The lines connecting the frames (lead reinforced mooring ropes with a minimum break load approximately 4500 kg) were attached through small holes on each arm to maintain the spread, prevent tangling and stop the lines from compressing the frames whilst under tension. As with the steel frames, the line spacers were coated in interzone 954 to prevent corrosion.

Figure 8 Steel line spacer. The anchor or buoy was tied to the spacer through the large hole in the centre, whilst the ropes connecting the frames were run through the small holes on each arm.

It was planned that the recovery of the arrays would be from the anchor after 6 - 8 months of exposure. The recovery line (figure 4) was to be pulled aboard and connected to a winch. The anchor would then have been winched up to the vessel, allowing the subsurface buoy to float to the surface along with the frames. However, the strength of the mooring ropes proved to be insufficient. During a period of extreme weather and strong winds the ropes failed and the moorings broke away from the anchors. Two of the arrays were recovered but had been damaged and appeared to have been dragged along the seabed, removing the anti-corrosion coating and, most likely, epibiota from the surfaces. Thus, epibenthic data could not be recovered.

1.3.2 Collaborative research

The effects of epibenthic growth on the fatigue life, defined as the number of loading (stress) cycles a structure can sustain before failure (Xin, 2013), of an offshore wind turbine was evaluated through parametric finite element analysis (FEA) modelling of a monopile support structure. Two case studies were performed; the first focused on the effects of variability with respect to depth, referred to as zonation, and the second focussed on the effects of the thickness of colonising layers. Models were quantified with potential colonising profiles and thicknesses based on published data. The key ecological contribution made to this study was to demonstrate that the thickness of the biomass and the rate of colonisation and growth is highly dynamic, rather than linear across the structure, which is a common assumption made by engineers. As the thickness of the layer of marine organisms increased, the turbine fatigue life was shown to decrease. The reduction in fatigue life varied between roughly 52-59% in accordance with variability in the thickness of biofouling. Thus, as epibenthic communities are dynamic and vary across the life of a turbine the rate of fatigue would also vary across the life of the turbine. The results of this study were published in the proceedings of the 6th International Conference On Marine Structures (Martinez-Luengo et al., 2017). The publication of this study is presented in annex A.

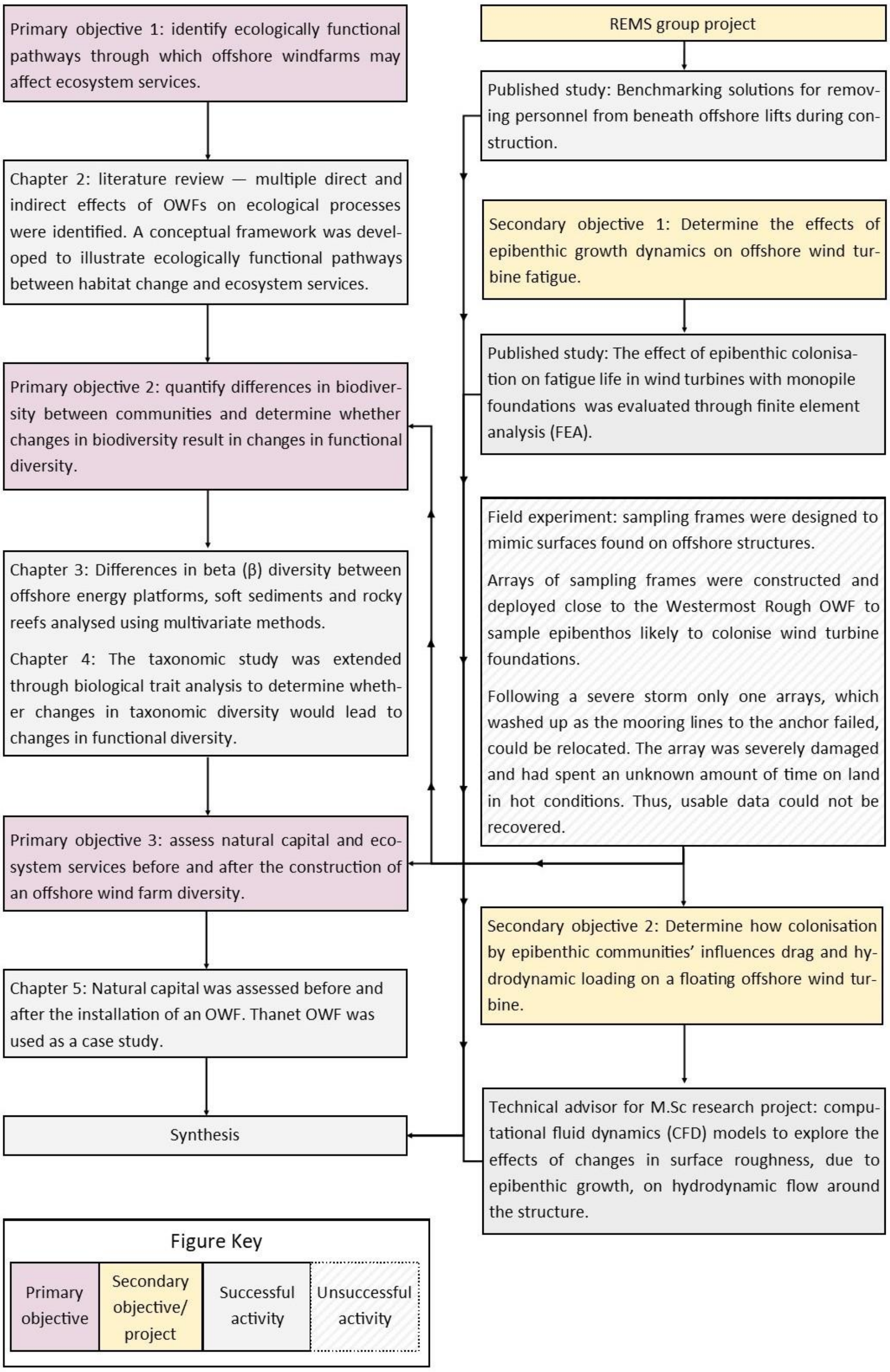
In addition, as part of the REMS PhD programme I contributed to a group project in which solutions for removing personnel from beneath offshore lifts during construction was evaluated by means of multi-criteria decision analysis. Technical support and data for dropped-object incidents during offshore wind turbine construction was provided by the offshore wind health and safety organisation G+. The results of this study were published in the journal Energies (Richmond et al., 2018) and the Journal of Physics: Conference Series (Leimeister et al., 2018). Moreover, an executive report was produced and submitted to G+ for dissemination to industry partners. The publications related to this study are presented in annexes B, C and D.

1.3.3 M.Sc. project technical advising

Along with a colleague, a structural engineering PhD researcher, I proposed an M.Sc. research project to study effect of epibenthic communities on drag and hydrodynamic loading on a floating offshore wind turbine. By changing the dynamic regime around floating structures and mooring systems, colonisation may influence hydrodynamic loading on foundations, and effect the stability of floating turbines. For this project my colleague and I were subject advisors. The MSc student developed computational fluid dynamics (CFD) models to explore the effects of changes in surface roughness, due to epibenthic growth, on hydrodynamic flow around the structure. The models were validated against published data from studies on artificially roughened surfaces. The results of this project indicate that even for a small degree of epibenthic growth drag coefficients are greatly affected. However, CFD was only shown to be effective in modelling hard colonising species, such as mussels and barnacles (Saiz-Pascual, 2018). For soft bodied species, such as macroalgae, porifera and hydroids, the drag effects could not be determined (Saiz-Pascual, 2018).

1.4 Research work flow

Figure 9 illustrates the flow of work conducted to address the primary and secondary objectives, and the group project. Work related to the primary objectives have been presented in the main body of this thesis; chapters have been clearly linked with the primary objectives they address. The secondary objectives have been linked with the studies and research projects that were conducted parallel to my main research.



Primary objective 1: identify ecologically functional pathways through which offshore windfarms may affect ecosystem services.

Chapter 2: literature review — multiple direct and indirect effects of OWFs on ecological processes were identified. A conceptual framework was developed to illustrate ecologically functional pathways between habitat change and ecosystem services.

Primary objective 2: quantify differences in biodiversity between communities and determine whether changes in biodiversity result in changes in functional diversity.

Chapter 3: Differences in beta (β) diversity between offshore energy platforms, soft sediments and rocky reefs analysed using multivariate methods.

Chapter 4: The taxonomic study was extended through biological trait analysis to determine whether changes in taxonomic diversity would lead to changes in functional diversity.

Primary objective 3: assess natural capital and ecosystem services before and after the construction of an offshore wind farm diversity.

Chapter 5: Natural capital was assessed before and after the installation of an OWF. Thanet OWF was used as a case study.

Published study: Benchmarking solutions for removing personnel from beneath offshore lifts during construction.

Secondary objective 1: Determine the effects of epibenthic growth dynamics on offshore wind turbine fatigue.

Published study: The effect of epibenthic colonisation on fatigue life in wind turbines with monopile foundations was evaluated through finite element analysis (FEA).

Field experiment: sampling frames were designed to mimic surfaces found on offshore structures.

Arrays of sampling frames were constructed and deployed close to the Westermost Rough OWF to sample epibenthos likely to colonise wind turbine foundations.

Following a severe storm only one arrays, which washed up as the mooring lines to the anchor failed, could be relocated. The array was severely damaged and had spent an unknown amount of time on land in hot conditions. Thus, usable data could not be recovered.

Secondary objective 2: Determine how colonisation by epibenthic communities' influences drag and hydrodynamic loading on a floating offshore wind turbine.

Technical advisor for M.Sc research project: computational fluid dynamics (CFD) models to explore the effects of changes in surface roughness, due to epibenthic growth, on hydrodynamic flow around the structure.

Figure 9 Diagram showing the workflow of this thesis and additional projects as part of the REMS doctoral training. Primary objectives are shown in red boxes and secondary objectives are in yellow boxes. The grey boxes show activities undertaken to meet the objectives.

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Chapter 2: Linking Ecosystem Services With Epibenthic Biodiversity Change Following Installation of Offshore Wind Farms

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2.1 Introduction

A growing awareness of the effects of climate change and concerns over energy security have been driving forces for renewable energy (Mangi, 2013; Szulecki et al., 2016; Voormolen et al., 2016). Owing to much larger installed turbines, as well as the stronger, more consistent winds offshore, offshore wind farms (OWFs) have a higher potential to harness renewable energy than their terrestrial counterparts (Lange et al., 2010; Petersen and Malm, 2006). As a result, the offshore wind energy industry has seen considerable investment. In European waters, the cumulative installed capacity of OWFs rose from 0.8 GW in 2006 to 12.6 GW by the end of 2016 (Corbetta and Miloradovic, 2016). The European offshore wind industry is expected to continue to expand and may contribute more than 10% of Europe's energy (around 140 GW) by 2030 (Langhamer, 2012; Zervos et al., 2009). Growth has been slower outside of Europe, but substantial expansion is still expected. Japan's cumulative installed offshore wind capacity was 59.6 MW by the end of 2016 with around 2.5 GW more in various stages of development (GWEC, 2016). In China and North America, offshore wind capacity is expected to achieve 5 GW (up from 1.6 GW in 2015) and 10 GW by 2020 respectively (GWEC, 2016; Lü et al., 2017; Zhao and Ren, 2015). That expansion is set to increase in North America to 54 GW by 2030 (Zhao and Ren, 2015).

Whilst it is largely accepted that OWFs provide net benefit to the global environment by reducing direct CO_2 emissions, it is not clear how large-scale installation of OWFs may influence local ecosystems. Modification of marine habitat following the installation of an OWF is expected to change local and regional biodiversity. Key ecosystem processes are supported by biodiversity, which are crucial to the delivery of multiple functions that affect the provision of ecosystem services (Mace et al., 2012; Snelgrove et al., 2014; Wilhelmsson and Malm, 2008). Ecosystem services are goods and benefits humans derive from nature, emphasised as components of wealth, well-being and sustainability (Carpenter and Turner, 2000; Costanza et al., 2014a; Liquete et al., 2013; Mace et al., 2012). Identified as provisioning (e.g. food), regulating (e.g. carbon sequestration), cultural (e.g. tourism and recreation) and supporting (e.g. nutrient cycling) (Beaumont et al., 2007; Reid et al., 2005); they are, in essence, by-products of ecosystem processes and functions that are recognised as being beneficial to people, particularly in relation to health and well-being (Sandifer et al., 2015). Such processes and functions are supported by biodiversity at local and regional scales.

It is generally considered that high biodiversity supports high ecosystem functionality, with declines in biodiversity having a negative effect on ecosystem functions (Balvanera et al., 2006; Cardinale et al., 2012; Gamfeldt et al., 2015; Hooper et al., 2005; Lefcheck et al., 2015; Loreau et al., 2001). For instance, ecosystems with high biodiversity typically have greater resistance to disturbance (Isbell et al., 2015; Purvis and Hector, 2000; Tilman et al., 2006). Worm et al (2006) support this observation; they demonstrated that lower rates of collapse and higher rates of recovery in commercially important fisheries occurred where there was higher regional species richness. It has been suggested that the presence of species with similar ecological roles and traits effectively provides biological redundancy and protects against changes to ecosystem function (Duarte, 2000; Levin, 1999; Palumbi et al., 2009). Thus, a reduction in species richness could result in an ecosystem that is less resilient. Whereas increased biomass and biodiversity due to introduced hard substrate may create resilience in epibenthic populations, which may further support higher trophic levels.

In recent decades, ecosystem services have become a major area of research, development and policy attention in terrestrial systems (Naidoo et al., 2008). In marine environments however, ecosystem services have received less attention, beyond fisheries and related industries (Gee and Burkhard, 2010; Liquete et al., 2013) and only recently have the effects of OWFs on the delivery of ecosystem services been studied (Busch et al., 2011; Hattam et al., 2015; Mangi, 2013; Wilding et al., 2017). However, linkages have not been made between biodiversity, ecosystem functions, and ecosystem services. With the evident expansion of offshore wind energy across the world there is a common need to consider how the associated large-scale habitat modification, through the installation of OWFs, and subsequent changes to biodiversity, could affect the provision of ecosystem services. Determining how changes in biodiversity would impact processes and functions is central to determining the effect of OWFs on the delivery of associated ecosystem services. As such, this review aims to specifically link changes to biodiversity, in relation to OWFs with ecosystem services through associated processes and functions.

2.2 Habitat modification by offshore wind farms

By introducing hard substrate in the form of the turbine towers, foundations, cables and scour protection, OWFs increase the complexity of the seabed and the water column and present opportunities for food and shelter for benthic associated organisms at various life stages (Coates et al., 2011; Langhamer, 2012; Petersen and Malm, 2006). Thus, in effect OWFs act as artificial reefs, increasing local biomass and promoting biodiversity (Langhamer, 2012; Mangi, 2013). This is not unexpected; hard substrate in the marine environment, such as OWFs and oil and gas platforms, have been shown to be rapidly and intensively colonised by epibenthic species (Connell and Slatyer, 1977; Degraer et al., 2012; Kerckhof et al., 2012, 2010, 2009). Indeed, artificial structures, including shipwrecks, sea walls, oil and gas platforms and purpose built artificial reefs, have been shown to support diverse reef communities (Forteath et al., 1982; Guerin et al., 2007; Lengkeek et al., 2013; Mallat et al., 2014; Schrieken et al., 2013; Whomersley and Picken, 2003; Wolfson et al., 1979; Zintzen and Massin, 2010). In the southern North Sea, up to 250 taxa have been recorded on shipwrecks, which was similar to the species richness recorded by soft substrate surveys of the entire Dutch continental shelf (Daan and Mulder, 2006; Lengkeek et al., 2013; Schrieken et al., 2013). In addition, fish species are known to aggregate around hard-structures largely due to the provision of food through the development of species rich epifauna-communities (Reubens et al., 2011; Svane and Petersen, 2001). Atlantic cod, *Gadus morhua*, have shown a preference for hard substrate habitats and it has been noted that close proximity to shipwrecks provides protection from bottom trawl fisheries (Lengkeek et al., 2013).

Fish, including commercial species, have been shown to aggregate around wind turbine foundations (Reubens et al., 2013, 2011), which may have added benefits for exploited populations. As offshore wind turbine foundations present a hazard to fishing gear they may, over time, encourage recovery of commercially exploited fish stocks and lead to over-spill to surrounding areas (Busch et al., 2011; Langhamer, 2012; Lengkeek et al., 2013). However, evidence of benefits of OWFs to fisheries have so far been inconclusive. In the North Sea, reported catches before and after the construction of Kentish Flats and North Hoyle wind farms showed no significant changes, although catch per unit effort (CPUE) from survey trawls within the Kentish flats wind farm were higher for all species except sole (Mangi, 2013).

Typically, wind turbines have been installed in regions characterised by a soft sandy benthic environment, such as the North Sea, where hard substrate and intertidal regions are uncommon (Hooper et al., 2015; Kerckhof et al., 2011; Lengkeek et al., 2013; Mangi, 2013). Therefore, OWFs represent a large-scale increase in local habitat heterogeneity that may lead to a regional shift from sediment associated benthic to hard bottom and intertidal communities (Kerckhof et al., 2011; Lengkeek et al., 2013; Mangi, 2013). Indeed, several studies have indicated that epifauna assemblages found on artificial reefs, including wind turbine piles, differ from those on nearby reefs and natural substrate (Connell and Glasby, 1999; Petersen and Malm, 2006). Moreover, there is evidence artificial reefs may act as stepping stones for non-native species (De Mesel et al., 2015; Gill, 2005; Glasby et al., 2007). Kerckhof et al (2011) demonstrated that OWFs in the Southern North Sea were rapidly colonised by non-indigenous species, particularly in the intertidal region.

The introduction of epibenthic assemblages can also modify the local hydrodynamic regime, biochemistry and benthic sediment composition (Boehlert and Gill, 2010; Coates et al., 2011; Miller et al., 2013; Vaissière et al., 2014). Hiscock et al (2002) suggested that alteration of local hydrodynamic regimes may lead to turbulences that cause resuspension of fine sediments, reducing light penetration and smothering existing benthic communities.

There is concern around the potential for this large-scale reef effect to modify marine ecosystems (Langhamer, 2012; Petersen and Malm, 2006) as OWF developments introduce an significant hard substrate surface area to a previously open water and an often sedimentary sea bed habitat (Boehlert and Gill, 2010; Coates et al., 2011). To date, on European coastlines, more than 3500 turbines have been installed (Byrne et al., 2017). It is important to note that OWFs differ from other structures in that modification of the local environment spans multiple devices. Expressly, rather than a single large reef, an OWF represents a network of interconnected smaller artificial reefs. A single turbine has a relatively small ecological footprint. To illustrate, recent monopile designs have a diameter of 8 m (Byrne et al., 2017), leading to a footprint on the seabed of 50.3 m^2 (not including scour protection). Jacket foundations have a larger footprint. For example, a foundation with a base of 20 m (Seidel, 2007) would have a footprint of 400 m^2. However, this remains relatively small when compared with that of an OWF array, which may be several square kilometres with turbines separated by distances of 500-1000m (Snyder and Kaiser, 2009). Many of the proposed larger developments with hundreds of turbines will have footprints of several hundred square kilometres (Boehlert and Gill, 2010; Gill, 2005).

Changes to the habitat on the scale of a single turbine may have minor effects in isolation, but cumulative effects across the scale of an OWF may be substantial and are, at present, highly uncertain (Willsteed et al., 2017). The level of complexity and variation would make scaling ecosystem services across OWFs and estimating cumulative impacts very challenging. There would be variations in local conditions, such as hydrodynamic regime. Additionally, the installation of OWFs span across seasons. As a result, the oceanographic conditions and species richness in the water column would vary between turbine installations. As such, it is likely that multiple stages of development may be seen on turbine substructures within a single OWF. Further, as with any natural reef, communities on turbine substructures will change and adapt over time. Therefore, it is not unreasonable to expect the delivery of ecosystem services to vary over the lifespan of turbines.

Based on existing evidence it is expected that the OWFs would dramatically change local biodiversity, and hence the associated ecosystem processes and functions. It is important to understand the causes and effects that lead to these changes which manifest themselves in terms of their biological or ecological significance to truly determine the impact on the local environment. However, determination of the significance of the environmental impacts related to these changes are often not fully realised (Boehlert and Gill, 2010).

2.3 Offshore wind farms and benthic ecosystem dynamics

Epibenthic colonisation is a multistage process that begins at the microbial scale. Immediately following immersion dissolved macro-molecules adhere to the substrate, forming a thin conditioning film (Cooksey and Wigglesworth-Cooksey, 1995; Dobretsov et al., 2006; Melo and Bott, 1997; Qian et al., 2003). Within hours bacteria attach to the adsorbed layer of organic material (Melo and Bott, 1997) . These are followed by microscopic eukaryotes, such as diatoms, fungi and other heterotrophic eukaryotic organisms which, along with bacteria, begin to form biofilms (Dobretsov et al., 2006; Qian et al., 2007). The presence of biofilms has been described as a cue for colonisation, in that may encourage or deter larval and spore settlement (Dobretsov, 2010; Qian et al., 2007).

Colonisation is spatially dynamic, influenced not only by environmental variability but also structural characteristics of the substrate (De Mesel et al., 2015). It has long been understood that marine organisms occupy distinct bands above and below the waterline (Southward, 1958; Stephenson. T. A. and Stephenson. A., 1949; Whomersley and Picken, 2003). This pattern of zonation is a result of localised environmental characteristics forming fine scale habitats. Similar patterns have been found on existing offshore structures, such as offshore oil and gas platforms where studies of epibenthic communities have described patterns of zonation in relation to depth (Forteath et al., 1982; Guerin et al., 2007; Mallat et al., 2014; Wolfson et al., 1979). Not unexpectedly, recent studies have also described zonation on offshore wind turbine foundations (De Mesel et al., 2015; Kerckhof et al., 2009).

Spatial orientation is considered a major determinant of heterogeneity in colonising communities (Bourget et al., 1994; Bulleri and Chapman, 2004; Glasby, 2000; Glasby and Connell, 2001; Moura et al., 2008). Indeed, epibenthic assemblages have been shown to differ with spatial orientation on natural rocky substrate and artificial surfaces, including panels, shipwrecks, pontoons, pilings, and oil and gas platforms (Baynes, 1999; Connell and Anderson, 1999; Connell and Glasby, 1999; Forteath et al., 1982; Fuller, 1946; Todd and Turner, 1986; Wendt et al., 1989; Withers and Thorp, 1977). Moreover, there is evidence that some species preferentially settle, or have greater survival rates, on surfaces with particular orientation. Moura et al (2008) found that on horizontal surfaces of experimental cubes the sessile epibenthic assemblages were dominated by cirripeds, predominantly *Amphibalanus amphitrite* (previously reported as *Balanus amphitrite* by Moura et al (2008). Similarly, Connell and Glasby (Connell and Glasby, 1999) found that assemblages on vertical surfaces of pontoons differed from those attached to horizontal undersides (Connell, 1999). Several studies have also shown barnacles, bryozoans, and some sponges tend to be more abundant on suspended substrata, whereas algae are more dominant on fixed substrata (Fuller, 1946; Glasby and Connell, 2001; Withers and Thorp, 1977).

Several wind turbine foundation designs are in commercial use, which vary in shape, size and materials. Variation in substratum characteristics between structures may create different initial conditions for biofilm development, which is likely to influence the subsequent stages of colonisation (De Mesel et al., 2015). Additionally, scour protection used around wind turbine foundations add complexity and provide further habitat.

Table 1 compares epibenthic communities found on a monopile and jacket substructure from published literature (Bouma, 2012; Hiscock et al., 2002; Krone et al., 2013b). It should be noted, however, that structures included in these studies differed not only in foundation type but also age, location and installation season; factors that can also influence the development of epibenthic communities. Nonetheless the choice of foundation for turbines may create different opportunities for colonising organisms within an OWF. Indeed, greater complexity in jacket foundations, with structures in multiple orientations, as well as sheltered and shaded surfaces, is likely to provide a very different habitat from monopiles.

Floating turbines are an emerging technology that has not reached the commercial market. Empirical and monitoring data from colonising communities are absent. As such the illustration in table 1 was produced using published data from buoys and deep water oil rigs (Forteath et al., 1982; Macleod et al., 2016; Southgate and Myers, 1985).

Although a floating spar may appear similar in shape to a monopile there are key differences in the habitat they create. As a floating structure that rises and falls with the tide, a spar would not introduce a true intertidal zone. Therefore, it is unlikely that substantial intertidal community would be present above the water line. Although there would be a splash zone and those species present would be able to survive long periods of desiccation. In addition, as the structure is not in contact with the benthos scour protection would not be required. Rather, the spar would be kept in place through moorings. However, mooring lines and the cables would also be colonised by epibenthic organisms.

Over a large OWF the foundation type could have important implications for habitat modification, which would affect biodiversity, ecosystem function, and subsequently the delivery of ecosystem services.

Table 1 Expected offshore wind turbine epibenthic community profiles for different turbine structure designs using examples from European seas based on published literature (Bouma, 2012; Hiscock et al., 2002; Krone et al., 2013). Dashed lines show depths at which communities change.

Depth	Monopile		Jacket		Floating	
	Representative Taxa	Example Species from Europe	Representative Taxa	Example Species from Europe	Representative Taxa	Example Species from Europe
Intertidal/ Splash	Ephemeral algae	*Ulva lactuca and Ulva intestinalis*	Ephemeral algae	*Ulva lactuca* and *Ulva intestinalis*	Ephemeral algae	*Ulva intestinalis*
	Red foliose algae	*Porphyra* spp.				
	Barnacles	*Semibalanus balanoides and Austrominius modestus*	Barnacles	*Semibalanus balanoides* and *Austrominius modestus*	Red foliose algae	*Porphyra* spp.
	Oysters	Mainly *Crassostrea gigas,* but also *Ostrea edulis*				
	- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -
0 metres	Mussels	*Mytilus edulis*	Mussels	*Mytilus edulis*	Ephemeral algae	*U. lactuca* and *U. intestinalis*
	Crustaceans	Unspecified				
	Anemones	Diadumene cincta and Metridium dianthus	Anthozoa	*Hexacorallia* spp.	Red algae	*Polysiphonia brodiei*
	Sponges	*Halichondria panicea*	Red algae	Unspecified	- - - - - - - -	- - - - - - - -
5 metres	Hydroids	*Ectopleura larynx*			Red algae	*Polysiphonia stricta*
	Sea stars	*Asterias rubens*			Hydroid	*Ectopleura larynx* (associated with algal growth)
	- - - - - - - -	- - - - - - - -	Sea urchin	*Psammechinus miliaris*		
	Mussels	*M. edulis*			Crustacean	*Jassa falcata* (associated with algal growth)
					Mussels	*Mytilus edulis*
10 metres	Crustaceans	Unspecified	Sea star	*Asterias rubens* (low abundance)	Anemones	*Metridium dianthus* and *Sagartia troglodytes*
			- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -

			Mussels	*M. edulis*		
	Anemones	M. dianthus, D cincta and Sagartia elegans (the latter two in lower abundance)	Anemones	*M. dianthus*	Mussels	*M. edulis*
15 metres			*Hexacorallia*	Unspecified		
	Soft corals	*Alcyonium digitatum*				
			Brittle stars	*Ophiothrix fragilis*		
			Sea stars	*A. rubens*	Anemones	*M. dianthus* and *S. trolodytes*
	Hydroids	*Obelia* spp., *Kirchenpaueria pinnata* and *Tubularia indivisa*				
			Crabs	*Cancer pagurus* and *Necora puber* (the latter below 15 metres)		
20 metres						
	Sponges	*Amphilectus fucorum*				
			Anemones	*M. dianthus*	Anemones	*M. dianthus* (20-80 metres with max abundance approx 25 metres)
	Solitary sea squirts	*Ascidiella* spp.				
25 metres	Sea stars	*A. rubens*	*Hexacorallia*	*Unspecified*	Serpulid worms	*Spirobranchus triqueter* (20-80 metres may be interspersed with *M. senile*) and *Hydroides norvegica* (below approx 50 metres)

Scour protection / ≥30 metres	Sea urchins	*Psammechinus miliaris*	Crabs	*C. pagurus* and *N. puber* (the latter in low abundance)		
	Serpulid worms	*Spirobranchus triqueter*	Mussels	*M. edulis*	Soft corals	*Alcyonium digitatum* (particularly between 20-30 metres)
	Barnacles	*Balanus crenatus*				
	Bryozoa	Encrusting sea mats Large patches of bare substrate	Brittle stars	*O. fragilis*	Barnacles	*Chirona hameri* (below 75 metres)

2.4 Biodiversity and ecosystem function

Maintaining marine ecosystem health and function is essential to underpin our planet's life support systems (Mangi, 2013). Multiple direct and indirect effects on ecosystem processes and functions are expected following OWF installation (Gill, 2005). These can be linked to the delivery of ecosystem services. Figure 10 presents a conceptual schematic illustrating such relationships.

Direct effects include physical changes to the habitat from the installation of turbines and other structures. In figure 10, the blue dashed boxes on the left cover changes in hydrodynamic regime (Matutano et al., 2016), benthic habitat loss or gain and the provision of shelter from fishing and predation (Gill, 2005; Miller et al., 2013; Wilson and Elliott, 2009; Wilson et al., 2010).

Indirect effects, linked to the direct effects, include modification to processes and functions, and are shown by the series of boxes and arrows in the central, red section of figure 10. For example, complex epibenthic communities colonise turbine substructures forming artificial reefs (table 1) which can alter biodiversity and community structure, influencing processes and functions (Hooper et al., 2005; Schleuning et al., 2015). This reef effect can be linked to ecosystem services through several channels, indicated by the green dashed boxes on the right of figure 10. For instance, littoral fall, which is the deposition of faecal and other organic matter by epibenthic organisms colonising the turbine substructure, may enrich sediments, supporting soft-sediment communities (Coates et al., 2011, 2014; Köller et al., 2006; Maar et al., 2009). Feeding and bioturbation by benthic infauna contributes to the transfer of organic matter in to sediments and influences the rates of remineralisation and inorganic nutrient efflux (Aller, 1988; Christensen et al., 2000; Hansen and Kristensen, 1997; Kristensen, 2000; Lohrer et al., 2004; Welsh, 2010). Inorganic matter returned to the water column by bioturbating organisms influences primary productivity. Coates et al (2011) recorded higher Chlorophyll-a concentrations around a gravity based turbine than had been found in similar sandy-sediments. They noted that, in combination with a slight decrease in median grain size, increased productivity may enhance larval settlement and survival of certain macrobenthic species. This higher productivity and nutrient cycling are likely to have positive effects on the availability of food to higher trophic levels (figure 10), including commercially important species. Hence, changes in benthic and epibenthic biodiversity may well have knock on effects to food provision and cultural experience of iconic species, such as marine mammals or birds.

In the case of floating OWFs, owing to the greater operational depths, the time taken for organic matter from epibenthic communities to reach the seabed would increase. This is likely to result in the tidal currents spreading organic matter across a wide area and in a finer layer over the seabed. Thus, the localised effect of increased benthic habitat associated with floating OWFs may not be as pronounced as for their fixed counterparts. Alternatively, given consistent littoral fall, in time similar effects to organic matter deposition from fixed offshore wind turbines may become apparent over a wider area.

A further feature of the reef effect is the establishment of secondary or biologically mediated habitat (figure 10). For instance, mussel beds provide secondary habitat, increasing environmental complexity and providing further opportunities for feeding and shelter for motile species (Chapman et al., 2005; Krone et al., 2013b; People, 2006; Wilhelmsson and Malm, 2008; Witman, 1985). Witman (1985) found that outside of mussel beds population densities in benthic communities were reduced by 79%. Further there was a reduction in species richness and diversity in all functional groups except mussel bed infauna (Witman, 1985).

Although valued for its ability to support other goods and services, biodiversity is culturally appreciated for its existence irrespective other benefits derived from it (Mace et al., 2012). Determining the ecosystem service value of biodiversity may be unclear, but it intrinsically has plausible benefits, and this may then bring a new aspect to considering the advantages of OWFs. Busch et al (2011) illustrated possible benefits to human wellbeing from significant wind farm development. Interestingly, they identified conflicting views between stakeholders and highlighted ambiguity within the ecosystem services concept. Whilst installation of a physical structure also creates shelter from predation, turbine substructures are also an obstruction to fishing. Busch et al (2011) reported that the fishing community viewed OWFs as an barrier to fishing, whilst conservationists felt that, by reducing fishing access, OWFs could encourage the recovery of commercially exploited species (Busch et al., 2011; Federal Agency for Nature Conservation, 2004). In providing protection for migratory populations and juveniles, OWFs could support upper trophic biodiversity and allow overspill from commercially exploited populations to surrounding fisheries. This would support food provision to humans and cultural experiences, such as fishing or the enjoyment of wildlife (figure 10).

There has been suggestion of co-use of OWF for aquaculture of blue mussels (*Mytilus edulis*), oysters (*Ostrea edulis* and *Crassostrea gigas*) and algae (*Laminaria saccharina* and *Palmaria palmata*) (Hieronymus et al., 2004; Michler-Cieluch et al., 2009). It has been noted that without the foundations of wind turbines as anchor points, extensive aquaculture in the high-energy environment of the North Sea would not be possible (Hieronymus et al., 2004). Although currently a concept, should such co-use become a reality it may help change the attitudes of the fishing community towards OWFs.

Changes in epibenthic biodiversity are likely to be strongly linked with climate regulation and waste treatment (figure 10). Increased biodiversity and biomass due to the reef-effect around wind turbine substructures and scour protection may lead to greater storage of organic carbon (Lange et al., 2010). Through increased carbon storage OWFs could result in bottom up effects on climate regulation. Moreover, changes in biomass and biodiversity, such as the introduction of mussel beds, are likely to locally enhance water quality and waste treatment due to filter feeding (Hooper et al., 2017b; Lange et al., 2010). Yet, at present, the extent to which climate regulation and waste treatment may be altered by the introduction of OWFs is not known. Along with understanding chlorophyll-a as a measure of primary production, there is a need for empirical measurements of nutrient concentrations and the biomass of filter feeders in epibenthic communities on and around wind turbine substructures. A comparison of the cause-effect pathways leading to changes in primary productivity, nutrient concentration and filter feeding between OWFs and natural habitats, such as portrayed in figure 10, would go a long way towards elucidating these effects.

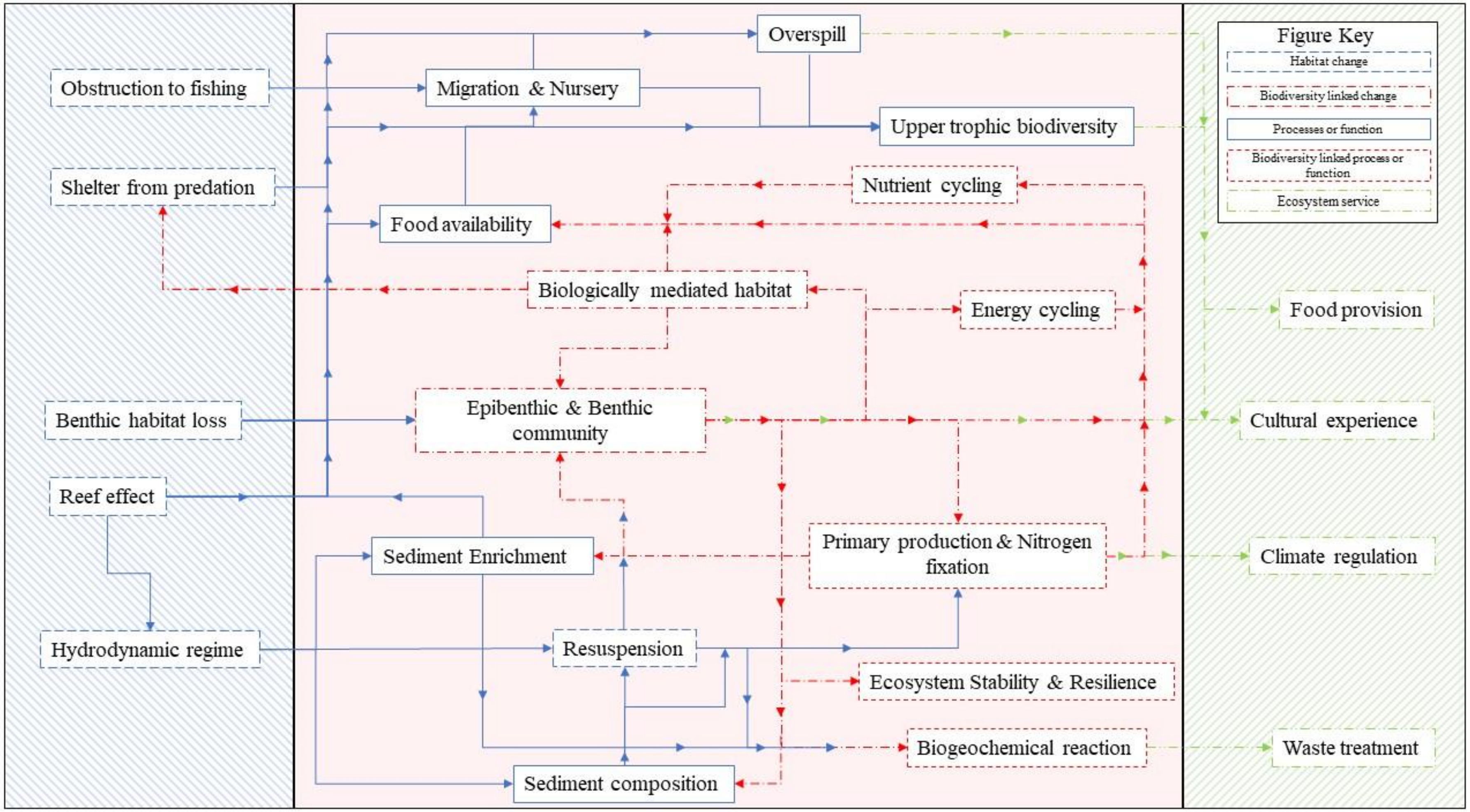

Figure 10 Biodiversity mediated linkages between habitat modification, ecosystem processes and functions, and the provision of ecosystem services in relation to offshore wind farm structures. Zones represent direct changes (blue hatching – left), secondary changes effecting processes and functions (red – centre), and linked ecosystem services (green hatching – right).

2.5 Conclusion

By linking changes in biodiversity with ecosystem services we have attempted to highlight potential benefits from OWFs beyond low CO_2 energy production. However, whether changes in biodiversity will have positive, negative or neutral effects on ecosystem services is unclear, as is the magnitude and extent of such effects.

As the offshore wind industry continues to expand, we can expect further large-scale modification of the marine environment. Empirical evidence is needed to gauge the scale of the effects of OWFs on biodiversity. However, it should be appreciated that ecosystem services are largely a product of natural processes and functions. Thus, to better understand how OWFs influence ecosystem services we must first consider their effects on functional diversity. Such insight could provide a mechanism for environmental monitoring programmes that are inclusive of ecosystem services and have clear objectives to predict positive as well as the negative impacts.

Chapter 3: Contrasting Epibenthic Diversity on Natural Substrate and Artificial Structures in the Energy Generating Area of the Southern North Sea

3.1 Introduction

The offshore energy industry is an important activity in the southern North Sea and has been over many decades. Oil and gas platforms were first introduced in the 1960s (Kerckhof et al., 2011). Over 1000 wells have been drilled and more than 150 platforms have been installed on the Dutch continental shelf alone (Daan and Mulder, 1996; Scheffers, 2016). In recent years offshore wind has gained traction in the global energy market, and offshore wind turbines are becoming increasingly common in the southern North Sea. With 63% of the global installation of Offshore Wind Farms (OWFs) in EU waters (Slavik et al., 2018), and with a combined capacity of around 11 GW (Heard et al., 2017) continued investment is expected. Projects under construction, in the pre-construction phase or consented in the southern North Sea may produce over 20GW per annum of electricity once in operation (4C Offshore, 2018). Figure 11 highlights the distribution and the spatial extent of OWFs that are planned, authorised or under construction in the area.

Offshore wind farms introduce multiple man-made structures, including turbines and substation foundations, cables and scour-protection (typically rocks and boulders) into marine environments (Degraer et al., 2010; Petersen and Malm, 2006; Whitehouse et al., 2011; Wilhelmsson, 2010). The combination of existing oil and gas structures and the newer OWFs represent an ongoing increase in man-made structures in the North Sea. Organisms colonise these man-made substrata, forming artificial reefs; a process that has been termed the reef-effect (Kerckhof et al., 2009; Langhamer, 2012; Langhamer et al., 2009). Artificial reefs have been shown to support diverse communities (Chambers et al., 2006; Dang and Lovell, 2000; Dobretsov et al., 2006; Melo and Bott, 1997; Prendergast, 2010; Qian et al., 2007). In the southern North Sea shipwrecks have added to the man-made structural habitat and as many as 250 epibenthic taxa have been recorded on them, which was similar to the species richness recorded by soft substrate surveys of the entire Dutch continental shelf (Dobretsov et al., 2006; Fusetani, 2004; Qian et al., 2007).

Offshore wind turbines differ from other artificial structures in the scale of their deployment as one wind farm has many turbines within its footprint. The extent of proposed developments, with hundreds of turbines, span several hundred square kilometres (Hooper et al., 2017; Lefcheck et al., 2015); an individual OWF may be seen as an interconnected network of artificial reefs which is repeated at other OWF sites (figure 11). It has been suggested that the reef-effect could be the most prominent change to a marine ecosystem following the installation of multiple OWFs (Petersen and Malm, 2006). As with oil and gas platforms, wind turbines also provide an intertidal zone where the structure meets the sea surface. Typically found along coastlines, the intertidal zone lies between the upper and lower extent of the tides and is characterised by a distinct pattern of vertical zonation in the colonisation by epibenthic species (Levington, 2001). Thus, turbines could present opportunities for intertidal species, such as those found on rocky shores, that would otherwise be unlikely to be found offshore owing to lack of hard, near-surface substrate (Kerckhof et al., 2011). Generally, on temporal rocky shores, from high up the shore to low, a black lichen zone, a littorine gastropod zone, a barnacle zone and finally a mussel zone (although the final zone may vary geographically) can be observed (Levington, 2001). Certainly, studies on oil and gas platforms and some early studies of offshore wind turbines have shown colonisation of the intertidal zone by mussels, *Mytilus* spp (Mallat et al., 2014; Southgate and Myers, 1985), barnacles, *Balanus crenatus, Balanus perforatus* and *Semibalanus balanoides* (Bouma, 2012; Kerckhof et al., 2010), green algae and red foliose algae *Ulva lactuca* and *Porphyra* respectively (Forteath et al., 1982), and, unexpectedly, the giant midge *Telmatogeton japonicus* (Kerckhof et al., 2010).

To date, most wind turbines have been built in shallow water on monopile foundations (4C Offshore, 2018; Slavik et al., 2018; Vandendriessche et al., 2015). However, many future projects, in pre-planning, planned or authorised phases are to be installed further offshore in deeper waters which are likely to use jacket structures (4C Offshore, 2018; Kerckhof et al., 2012; Slavik et al., 2018).

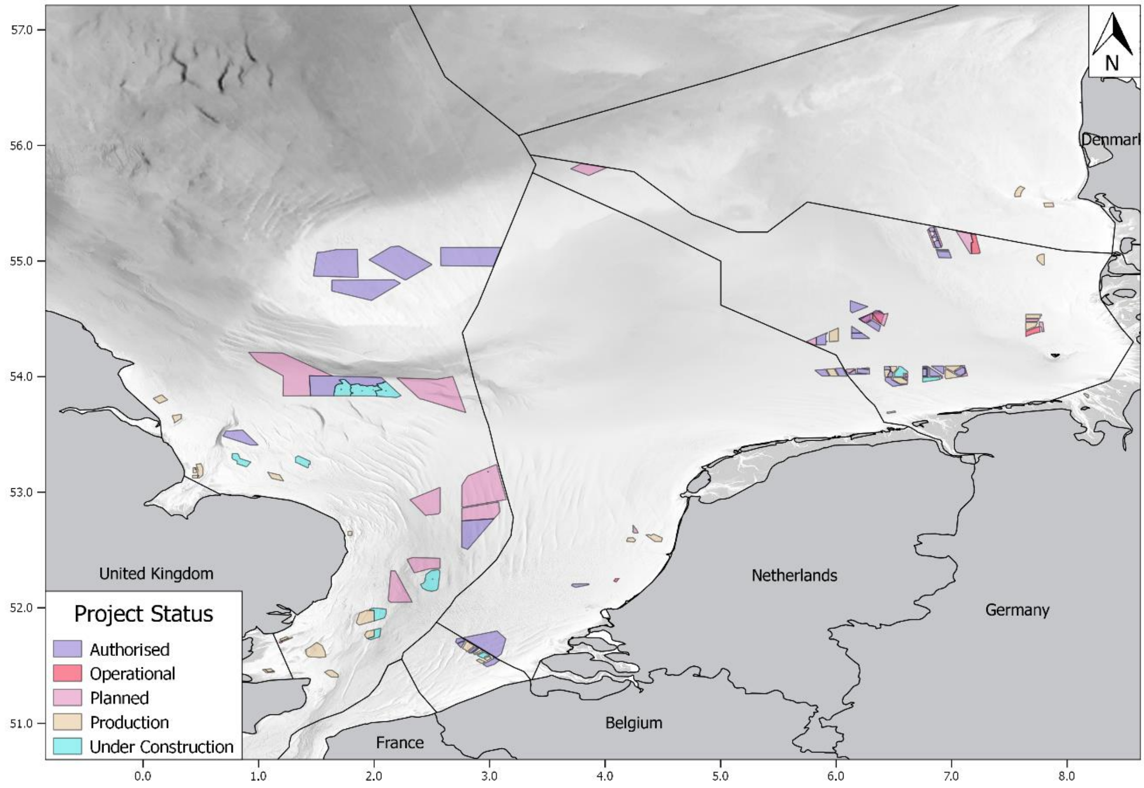

Figure 11 OWFs in the Southern North Sea, shown by their current project status. This figure was generated in QGIS version 2.18.13 using freely accessible OWF and bathymetry GIS data (EMODnet, 2018, 2015).

Reefs, defined as hard compact substrata on solid and soft bottoms, of biogenic concretions or of geogenic origin, which arise from the sea floor in the sublittoral (shallow coastal) zone and littoral (intertidal) zone (European Commission, 2013), are currently protected under the EU habitats directive (formerly the Council Directive) (European Commission, 1992). Whilst hard seabed and reefs are common around the coastal zone, they occur less frequently offshore, in the open sea (Coolen et al., 2015). The southern North Sea bed is dominated by soft sediment (Horn, 1974; Kerckhof et al., 2010; Lengkeek et al., 2013). Yet natural hard and/or immobile, substrate was once common; historical maps show 20-35% of the Dutch continental shelf was once covered by hard substrate, such as oyster beds, and immobile substrate, such as coarse peat banks (Lengkeek et al., 2013; Olsen, 1883; Whitehead and Goodchild, 1909). Oysters are important reef building species, providing habitat for entire ecosystems (Beck et al., 2011; Lenihan and Peterson, 1998). Largely due to over-exploitation there have been major losses of oyster beds from the North Sea (Franke and Gutow, 2004; Reise, 1982). Additionally, the tube dwelling *Sabellaria* were a major source of hard substrate in the North Sea. However, *Sabellaria* reefs have also been lost due to fishing activities (de Groot, 1984; Reise, 1982). Natural rock reefs can still be found in the Southern North Sea at the Hinder Banks, Cleaver Bank, the Texel Rough, Borkum Reef Grounds and Steingrund, near Helgoland (Coolen et al., 2015; de Kluijver, 1991; Veenstra, 1969).

It is understood that, by acting as artificial reefs, man-made structures effect biodiversity (Lengkeek et al., 2013). However, the extent that communities on artificial structures resemble those on natural reefs remains uncertain (Sanabria-fernandez et al., 2018; Van Der Stap et al., 2016). Although differences in community structure between natural and artificial substrates has been the subject of a number of studies (Ambrose and Swarbrick, 1989; Bulleri and Chapman, 2004; Knott et al., 2004; Perkol-Finkel et al., 2006; Sanabria-fernandez et al., 2018), it is difficult to generalise. Findings have thus far been inconsistent and dependent a number of factors, including location, interspecies interactions or characteristics of the artificial structure (Granneman and Steele, 2015; Hunter and Sayer, 2009; Sanabria-fernandez et al., 2018). For example, Sanabria-fernandez et al (2018) found that biodiversity was greater on natural reefs than on adjacent man-made breakwaters. They note that this was because of the decreased diversity in medium or low mobility species (such as sessile invertebrates or cryptic fish species).

Given that intertidal communities have been helped to colonise the offshore environment through the installation of artificial structures, and the tendency of species richness to increase with depth (Kerckhof et al., 2010), it is likely that structures which penetrate both the water column and the surface would change local epibenthic biodiversity. Changes in epibenthic biodiversity associated with OWFs is important to understand as biodiversity provides a range of natural processes and functions that support ecosystem services (Causon and Gill, 2018; Mace et al., 2012; Snelgrove et al., 2014; Wilhelmsson and Malm, 2008). For example, feeding and bioturbation by benthic infauna contributes to the transfer of organic matter in to sediments and influences the rates of remineralisation and inorganic nutrient efflux (Aller, 1988; Christensen et al., 2000; Hansen and Kristensen, 1997; Kristensen, 2000; Lohrer et al., 2004; Welsh, 2010). Thus, bioturbating organisms influence primary productivity, and in doing so support higher trophic groups including commercially important species. Moreover, suspension feeders, such as *Mytilus edulis*, have been shown to reduce local phytoplankton concentrations significantly (Dolmer, 2000; Maar et al., 2007). Thus, were turbine foundations to support large communities of *M. edulis*, as well as other suspension feeders, there could be a reduction in primary productivity around turbines within an OWF (Slavik et al., 2018).

With large scale of development, differences in benthic community structure have the potential to modify local community function and hence affect the delivery of ecosystem services. Therefore, the aim of this study was to determine if the biodiversity of epibenthic communities colonising energy structures in the southern North Sea reflects the community colonising natural substrate in the growing OWF dominated area.

3.2 Methodology

Data analysed in this study were from existing datasets made available for this research by the Centre for Marine and Coastal Studies Ltd (CMACS), Marine Ecological Surveys Ltd (MES), the Alfred Wegener Institute (AWI) and Wageningen University and Research (WUR).

A total of 10 sites were investigated, which consisted of soft sediments, naturally occurring rock reefs and artificial platforms (figure 12). The sites were selected due to their proximity to existing OWFs and are in areas where wind energy installations are expected to continue to increase, or in the case of the soft sediment sites, they were sites of future OWF installations. As can be seen from figure 12 the study sites are located in the UK, Dutch and German exclusive economic zones (EEZs).

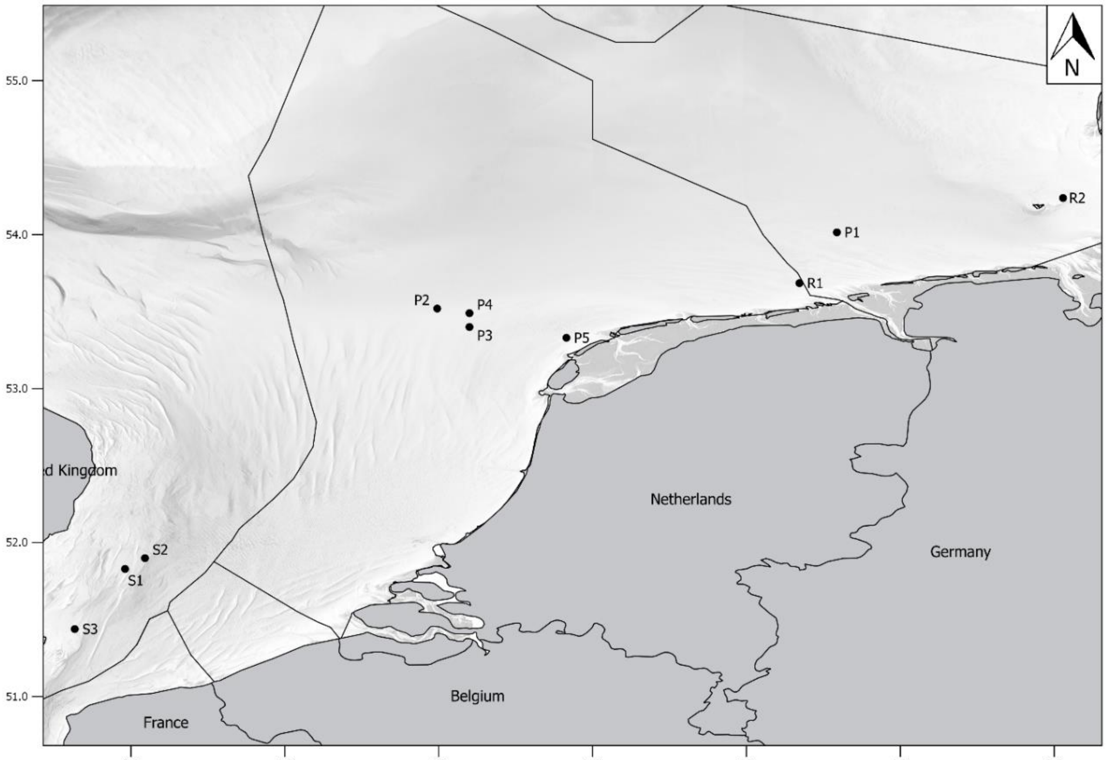

Figure 12 Southern North Sea survey sites. This figure was generated in QGIS version 2.18.13 using freely accessible bathymetry GIS data (EMODnet, 2018, 2015).

Table 2 shows the maximum water depth for each site and the distance from shore. The maximum water depth around the platforms (Px) was 32 m, and their distance from the coast was in the range of 41 to 104 km. For platforms P2, P3 and P4 cleaning had been carried out 7, 3 and 2 years prior to sampling respectively. During cleaning, colonising organisms were removed from the structures between 0-10 m depth. Cleaning had not taken place on P1 or P5.

The maximum depth at the natural reef sites was 28 m, which were 30 km (R1) and 50 km (R2) from the coast. The soft-sediment sites were 15-45 km from the coast with a maximum depth of 60 m.

Table 2 Site information. Distances were taken from GIS measurements in QGIS version 2.18.13. Longitude and latitude of sample sites/stations were available in the existing datasets. Measurements were taken from the nearest data point to land.

Site code	Site name	Substrate type	Min depth (m)	Max depth (m)	Distance from shore (km)
S1	Greater Gabbard Survey	Soft sediment	5	35	38
S2	Gallop Extension Survey	Soft sediment	6	60	43
S3	Thanet Survey	Soft sediment	2	49	15
R1	Borkum reef ground	Rock reef	28	28	30
R2	Helgoland Steingrund	Rock reef	9	17	50
P1	Fino 1	Platform	1	30	63
P2	K9-A	Platform	0	32	104
P3	L10-A	Platform	0	25	41
P4	L10-G	Platform	0	26	84
P5	L15-A	Platform	22	22	41

3.2.1 Soft sediment

Data from the Greater Gabbard (S1), Galloper (S2) and Thanet (S3) wind farm pre-installation benthic surveys (figure 13), conducted by the CMACS and MES, were obtained from the Marine Data Exchange (The Crown Estate, 2018). The intention of these surveys was to establish a pre-installation baseline of benthic communities. The sites are located in the Southern Bight, within the Outer Thames Estuary.

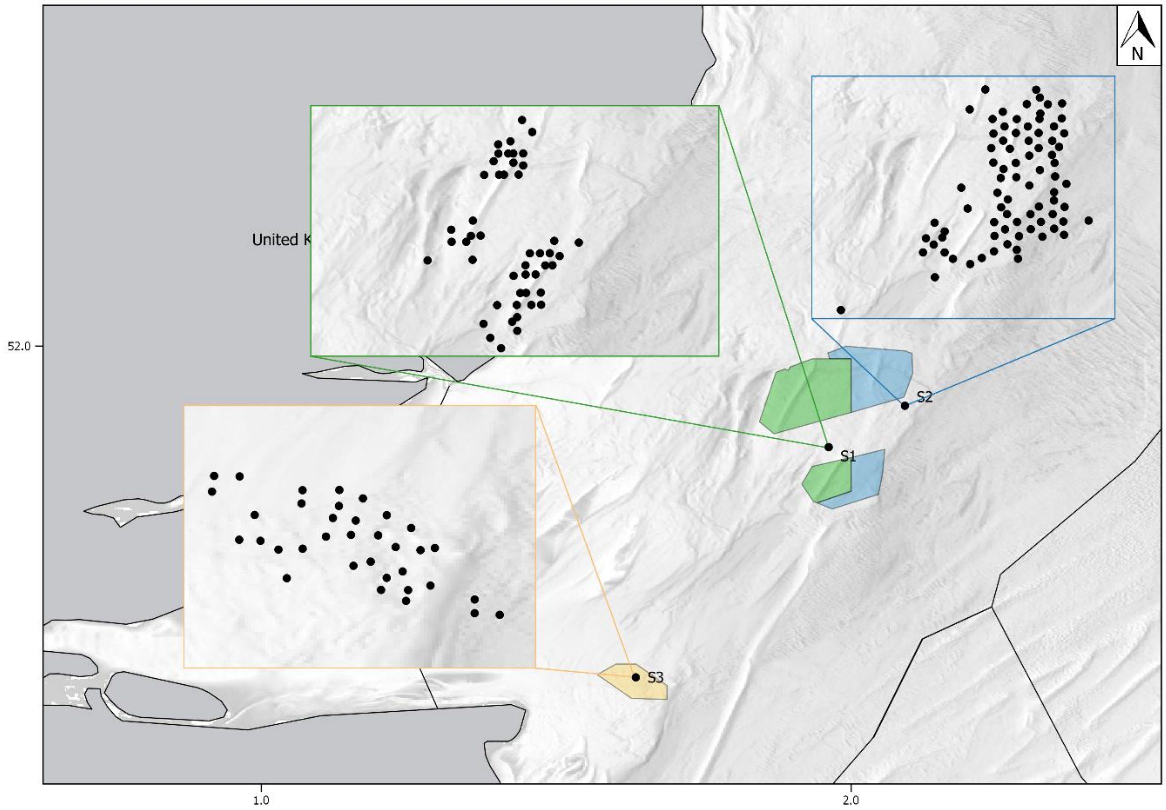

Figure 13 Soft sediment sites. Insets show locations of sampling stations for Greater Gabbard S1 (Green), Galloper S2 (Blue) and Thanet S3 (Yellow). This figure was generated in QGIS version 2.18.13 using freely accessible OWF and bathymetry GIS data (EMODnet, 2018, 2015).

Greater Gabbard wind farm was opened in 2013 (SSE, 2019). It consists of 140 turbines and has an extent of approximately 237 km^2 (181 km^2 on the Gabbard bank to the north and 56 km^2 on the Galloper bank to the south). Sediments in this region, shallower than the 20 m isobath, were dominated by sand on both banks (Neal, 2005). In areas deeper than 20 m the sediment was variable and patchy, and characterised by mud/clay, sand and gravels in various proportions (Neal, 2005).

Thanet wind farm was opened in 2010 (4C Offshore, 2018). Thanet consists of 100 turbines and has an area of approximately 35 km^2, and sediments in this region also generally consisted of sand, with varying levels of gravel and silt (Marine Ecological Surveys Ltd, 2008).

The Galloper extension wind farm, which opened in 2018 (Galloper wind farm ltd, 2019), consists of 56 turbines and has an extent of 183 km^2 (123 km^2 on the Gabbard bank to the north and 60 km^2 on the Galloper bank to the south). The sediments within this region were found to be dominated by medium and course sand, albeit with a significant proportion of gravel and shell (Neal, 2010).

Sampling was undertaken in November 2004 for S1; September and October 2009, and March 2010 for S2; and May and June 2005, with supplementary data from October and November 2007, for S3. Only samples taken within or near the wind farm footprint were retained for analysis whilst samples taken from the cable routes were removed from the dataset. Where stations were resampled, data were combined to provide the most complete view of species present. Of the data made available for this research, the final dataset included 90 samples from S1, 75 from S2, and 35 from S3.

The data from sites S1-3 were collected using a standard 10 cm^2 mini-hamon grab; samples were transferred to a tray and photographed (Marine Ecological Surveys Ltd, 2008; Neal, 2010, 2005). For all sites, samples were fixed in saline buffered formalin solution (approximately 5%) for transport to the laboratory (Marine Ecological Surveys Ltd, 2008; Neal, 2010, 2005). Once in the laboratory excess formalin was eluted and fauna were sorted in to their major taxonomic groups before being identified to the lowest achievable level under a stereomicroscope (Marine Ecological Surveys Ltd, 2008; Neal, 2010, 2005). Abundances were recorded, where possible, however colonial biota were recorded on a presence/absence basis (Marine Ecological Surveys Ltd, 2008; Neal, 2010, 2005). Sediment samples from were dried and sieved over the range of mesh sizes. For S1 mesh sizes ranged from 31.5 mm to <63 µm (Neal, 2005), for S2 the mesh sizes ranged from 63 mm to 63 µm (Neal, 2010), and for S3 the mesh sizes ranged from 64 mm to 63 µm (Marine Ecological Surveys Ltd, 2008). In all cases the sediment was classified based on the Wentworth scale (table 3). Sediment grain classifications <63 µm are also commonly referred to as muds (Bockelmann et al., 2017).

Table 3 Wentworth scale grain size classes for classifying sediments (Buchanan, 1984).

Wentworth scale	Sediment types
>256 mm	Boulders
64 - 256 mm	Cobble
4 - 64 mm	Pebble
2 - 4 mm	Granule
1 - 2 mm	Very coarse sand
0.5 - 1 mm	Coarse sand
250 - 500 µm	Medium sand
125 - 250 µm	Fine sand
63 - 125 µm	Very fine sand
<63 µm	Silt

In addition to grab sampling, direct observation of the seabed habitat was performed using drop down camera systems to check for biogenic reefs which could be damaged by intrusive sampling (Marine Ecological Surveys Ltd, 2008; Neal, 2010, 2005). The drop-down cameras used were a Kongsberg Simrad system at site S1, an aquatech Clearwater Camera system and a second unspecified camera system with similar specifications at S2, and an aquatech Weasel II at S3 (Gloyne-Phillips, 2004; Marine Ecological Surveys Ltd, 2008; Neal, 2010).

3.2.2 Natural rock reefs

The Borkum Reef Grounds (R1) are located north of the Wadden Sea island of Schiermonnikoog, covering an area of around 600 km^2 which extends across the German and Dutch border (Coolen et al., 2015). At 10 – 40 m, the seafloor is characterised by coarse sand, gravel and stone fields (Coolen et al., 2015). In addition, dense beds of *Lanice conchilega* have also been shown in the area, which may form an intermediate sand-reef system that provides habitat for species that occupy sand and rocky reefs (Coolen et al., 2015).

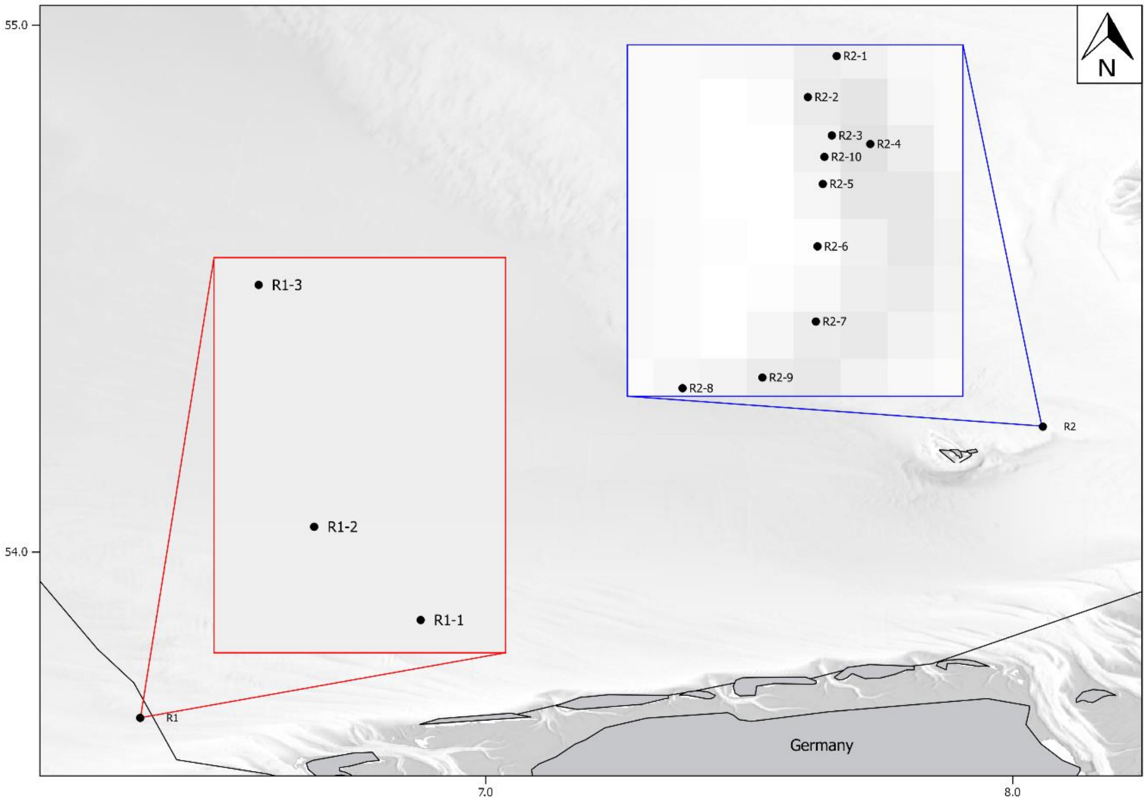

Figure 14 Rock reef sites. Insets show locations of stations for R1 (red) and R2 (blue). This figure was generated in QGIS version 2.18.13 using freely accessible OWF and bathymetry GIS data (EMODnet, 2018, 2015).

Researchers from WUR sampled benthic taxa from rock substrate from three stations in the Dutch zone of R1 between the 12th and 17th of August 2013 (figure 14). All samples were collected from rock substrate at 28 m depth. A SCUBA diver operated airlift sampler was used that was of similar design to that described by Barnett and Hardy (1967). The sampler was constructed from 50 mm PVC tubing ending in a 500 µm mesh net fed with compressed air (Coolen et al., 2015). A metal frame of 5 cm^2 was placed on the substrate and a putty knife attached to the sampler was used to remove all growth, which was sucked up through the PVC tubing and collected in the net (Coolen et al., 2015). Epifauna were relaxed in an oversaturated seawater menthol solution for at least 2 hours. Then samples were fixed in borax-buffered formalin-seawater solution (6%) for transport to the laboratory (Coolen et al., 2015). Excess formalin was eluted from the samples in the laboratory. After which samples were sorted in to their major taxonomic groups before being identified to their lowest achievable taxonomic level under a stereo microscope and counted (Coolen et al., 2015). Data made available for this research included 11 samples from site R1.

Steingrund (R2) is located north east of Helgoland in the German EEZ and is part of the Natura 2000 network (Site code: DE1714391) (Kühne and Rachor, 1996). It is a crescent-shaped reef of gravel and boulders, with a maximum depth of 14-18 m (Kühne and Rachor, 1996). The region supports diverse fauna and flora communities that overspill to surrounding areas and is an important feeding ground for bird species in the Helgoland seabird conservation area (Kühne and Rachor, 1996). It is in a relatively isolated position in the German bight, 50 km from the nearest mainland (de Kluijver, 1991).

Researchers from AWI conducted benthic surveys at R2 in August 2014 and 2015. The method of data collection at R2 differed from that at R1 and S1-3. During surveys divers placed 50 cm^2 quadrats in predetermined areas at each site. Fauna and flora within the transect identified to the lowest taxonomic level achievable in situ and counted (Dederer and Krone, 2015). A total of 10 stations between around 9 and 17 metres in depth were surveyed (figure 14). Data from both years were included for stations 2-8, but only data from 2015 were available for station 1, and data from 2014 for stations 9 and 10. Data made available for this research included 78 samples from R2.

3.2.3 Energy platforms

The energy platforms sampled K9-A, L10-A, L10-G and L15-A (P2-5 respectively), are part of a fleet of assets operated by ENGIE Exploration and Production Nederland B. V. (ENGIE). They were constructed between 1972 and 1999, and are supported by steel jacket foundations in water depths between 22 and 32 metres (Coolen et al., 2018). Data presented from P3 include samples from the production platform L10-AP and the riser L10-AR. These two structures are bridge linked (Anonymous, n.d.).

In 2014, steel sections of the structure and rocks (scour protection), were sampled by researchers from WUR. Sampling was performed using a similar method as for the R1 samples. A metal frame of 5 cm^2 was attached to the structures using magnets and scrape samples were taken with a putty knife and collected by airlift sampler in to a net with a 500 µm mesh (Coolen, 2017). Samples were taken at 5 m depth intervals, with three replicates taken at each interval (Coolen, 2017).

For P2, P3 and P4 samples were taken from steel members of the structure and the scour protection layer. Whereas samples from P5 were collected from the scour protection only. Scour protection consisted of rock dump and gravel around the foundation on the seabed. Samples of 5 cm^2 of rock and gravel were collected from the scour protection by hand and placed in a zip lock bag (Coolen, 2017). Data made available for this research included 19 samples from P2, 22 samples each from P3 and P4, and 3 samples from P5.

Samples were pre-processed onboard the research vessel. Epifauna were relaxed in an oversaturated seawater menthol solution for at least 5 hours (Coolen, 2017). Then samples were fixed in borax-buffered formalin-seawater solution (6%) for transport to the laboratory (Coolen, 2017). Excess formalin was eluted from the samples in the laboratory. Following which samples were sorted into taxonomic groups before they were identified to the lowest achievable taxonomic level under a stereo microscope (Coolen, 2017). Although data had originally been recorded in abundance, this proved to be labour intensive and impractical due to time constraints on the researcher, so later data was recorded as presence/absence only (personal correspondence).

3.2.4 Fino 1 research platform

Fino 1 (P1) is an unmanned research platform located in German waters in the immediate vicinity of the Alpha Ventus OWF, an area where further offshore wind development is planned (Anonymous, n.d.). It was built on a jacket foundation in a water depth of 30 metres; construction was commissioned in 2001 and completed in 2003 (Anonymous, n.d.).

Surveys of epibenthic communities on and around P1 were conducted between April and October from 2005 to 2007 by researchers from AWI. Scrape samples were taken and collected into 20 cm^2 nets with a 250 µm mesh size (personal correspondence). Samples were fixed in a borax-buffered formalin-seawater solution (4%) for transport to the laboratory (personal correspondence). In the laboratory, samples were weighed (wet weight), pre-sorted and preserved in 75% ethanol. Biota were sorted and identified to the lowest taxon possible and solitary taxa were counted. All samples from P1 were taken from steel members on each of the four legs of the structure. Sample depth ranges were categorised as 1 m (0-2.5 m range), 5 m (2.5-7.5 m range), 10 m (7.5-15 m range), 20 m (15-22.5 m), 25 m (22.5 – 27 m range) and 28 m (27-30 m range). Data made available for this research included 189 samples from P1.

3.2.5 Data handling

Community data were collected using multiple sampling methods (scrape sampling, grab sampling, drop down camera) and were of different sizes, as well as different data metrics (abundance, presence/absence, percentage coverage of substrate). Abundance data were not available for all samples. As such, all data were converted to presence/absence prior to analysis. Further, the number of sample locations was not consistent for all sites. The platforms were considered to be a single location with sample stations vertically distributed. Conversely sample stations from the rock reefs and soft sediments were distributed across the seabed.

Beta (β) diversity, defined as the extent that species composition between two or more locations differ (Magurran, 2004), was analysed at site level to determine differences in community composition. To avoid artificially inflating biodiversity by including multiple taxonomic levels when lower level representatives are available, only the lowest taxa level common to each site was retained. For instance, for the artificial platforms *Jassa* were identified to species level, e.g. *J. herdmani* and *J. marmorata.* However, in other datasets *Jassa* were identified to genus level only. As such, all records of *Jassa* were combined into a single column in the dataset identified as *Jassa* spp. Taxa were also checked against the World Registry for Marine Species (WoRMS) for up to date nomenclature.

3.2.6 Community analysis

To visualise the complex patterns inherent in the benthic community structure in a simplified form, ordination was used. Ordination is a multivariate statistical method; it can cope with multiple response variables, in this case multiple taxa. Non-metric multidimensional scaling (NMS) was considered the most appropriate ordination method for the data in this study as it is non-parametric and makes few assumptions about the nature of the data (Holland, 2008). Non-metric multidimensional scaling is performed on a dissimilarity matrix, where samples that share species in similar patterns and abundance have low dissimilarity, whereas samples that share few species with different patterns and abundance have high dissimilarity.

Non-metric multidimensional scaling ranks dissimilarities in community composition between samples in increasing order in n-dimensional space, whilst preserving distances as well as possible (Kruskal, 1964a). Thus, in NMS ordination plots, samples (represented by points) whose community composition are more similar are plotted closer together. Unlike for other methods of ordination, the axes do not represent specific variables. Rather they define an arbitrary cartesian coordinate system for plotting data (Kenkel and Burchill, 1990). Non-metric multidimensional scaling was performed with the metaMDS function in the vegan package in R. The dissimilarity matrix was calculated using Jaccard indices, which are binary and are appropriate for use with presence/absence data (Gardener, 2014).

Stress is the measure of goodness of fit for an NMS, and it increases with divergence from an increasing monotonic (entirely non-decreasing) relationship (Kruskal, 1964b). Stress is easily expressed as a percentage, and has been evaluated as 20%, 10 %, 5%, 2.5% and 0% representing a poor, fair, good, excellent and perfect fit respectively (Kruskal, 1964a).

Due to dataset's size, NMS of the full dataset could not converge to a clearly defined solution. As such, subsets were taken to perform separate ordinations to compare soft sediment and rock reef sites, soft sediment sites and platforms, and rock reef sites and platforms. However, even following the subset of data, initial attempts of NMS to compare soft sediment samples with those from natural rock reefs and platforms did not converge to a stable solution. This was due to a high proportion of site pairs with no shared taxa. It has been argued that a dissimilarity measure should take a constant value (typically 1) if sites have no species in common and the value 0 when sites have equal abundances of all species, and increase with increasing ecological distance (the Euclidean distances between sites on the gradient(s)) (Beals, 1984; Faith et al., 1987). However, these properties can be in conflict for long ecological gradients (high β-diversity) (De'ath, 2012). In accordance with the first property, multiple pairs of sites of varying separation will have no species in common but will have the same dissimilarity (De'ath, 2012).

De'ath (2012) outlined the extended dissimilarities approach to handling such conflicts in which the above properties are accepted as desirable but dissimilarities for site pairs that share no common species are modified. For those that share no species the dissimilarity is estimated by the sum of the dissimilarities with an intermediate site which shares species with each member of the pair of samples. As there can be many such sites the one with the minimum sum of dissimilarities is used (De'ath, 2012). This has been shown to be a robust method of accurately estimating ecological distances over long ecological gradients (De'ath, 2012), such as those that occurred between a number of soft sediment and rock reef samples.

For the soft sediment and rock sites, and soft sediment sites and platforms, site pairs with no common taxa were adjusted for NMS using the extended dissimilarities (Oksanen, 2018). Through this method, stable solutions were found for both ordinations.

Non-metric multidimensional scaling is a useful tool for visualising data and identifying patterns, however it is not a formal hypothesis test and cannot show the statistical significance of any observed differences. Therefore, one-way permutational multivariate analysis of variance (PERMANOVA) was performed to test whether differences observed in community structure were statistically significant. Permutational analysis of variance is a method of geometric partitioning that compares groups (in this case samples taken from different sites) and tests the null hypothesis that the centroids (the central location for a group) and dispersion of those groups are equivalent, and thus do not differ (Anderson, 2001).

Permutational multivariate analysis of variance is non-parametric in the one-way case (Anderson, 2001). It is ranked based and retains statistically robust properties of nonparametric multivariate methods, such as the flexibility to base the analysis on a dissimilarity measure and distribution free inferences achieved through permutations (Anderson, 2017). Thus, It makes no assumptions about the distributions of the original variables (taxa) or the dissimilarities (Anderson, 2017); it assumes only exchangeability of permutable units under a true null hypothesis (Anderson, 2017).

Permutational multivariate analysis of variance, based on a Jaccard dissimilarity measure, was performed using the Adonis function in the vegan package, with 100,000 permutations. Differences between sites were quantified using the full dataset. As PERMANOVA does not compare sites individually, pairwise contrasts were also calculated to identify significant differences between individual sites (Azbizu, 2017). In addition, differences between depths, substrate type and distance from shore were analysed using PERMANOVA with a reduced dataset, for which these variables were available. Substrate type included steel (from the platform struts and piles), rock (from the scour protection layer and reefs) and soft sediments.

All analyses were undertaken in the R language and statistical environment version 3.3.1 and R studio version 1.1.453, with the vegan package for multivariate analysis loaded. Graphics were also produced in R and R studio with the ggplot2 package for data visualisation loaded. The R code for the community analysis is presented in appendix A.

3.3 Results

3.3.1 Exploratory analysis

The final dataset contained 416 taxa from 19 Phyla, with the greatest number of taxa sampled from soft sediments (n=306), followed by artificial platforms (n=168) and natural rock reefs (n=112). Additionally, there were 210 unique taxa identified at soft sediment sites, 56 on artificial platforms and 31 on rock reefs. Soft sediment and rock reef sites shared 58 taxa, soft sediment sites and artificial platforms shared 89 taxa, and rock reefs and artificial platforms shared 61 taxa. Finally, 38 taxa were observed on all substrates. A comprehensive list of taxa and their presence on platforms and/or natural substrata is presented in appendix B (table B-1).

It should be noted that the increased number of taxa identified from soft sediment sites and offshore platforms, compared with rock reefs may be a product of sampling effort rather than a genuine difference in species richness. A total of 255 samples were taken from the offshore platforms. Whereas 200 and 189 samples were included from the soft sediment and rock reef sites respectively. Yet, the mean number of taxa recorded from soft sediments (1.5) did exceed the mean recorded from platforms and rock reefs (0.8 and 0.6 respectively). Thus, it appeared that the soft sediments had the greatest species richness.

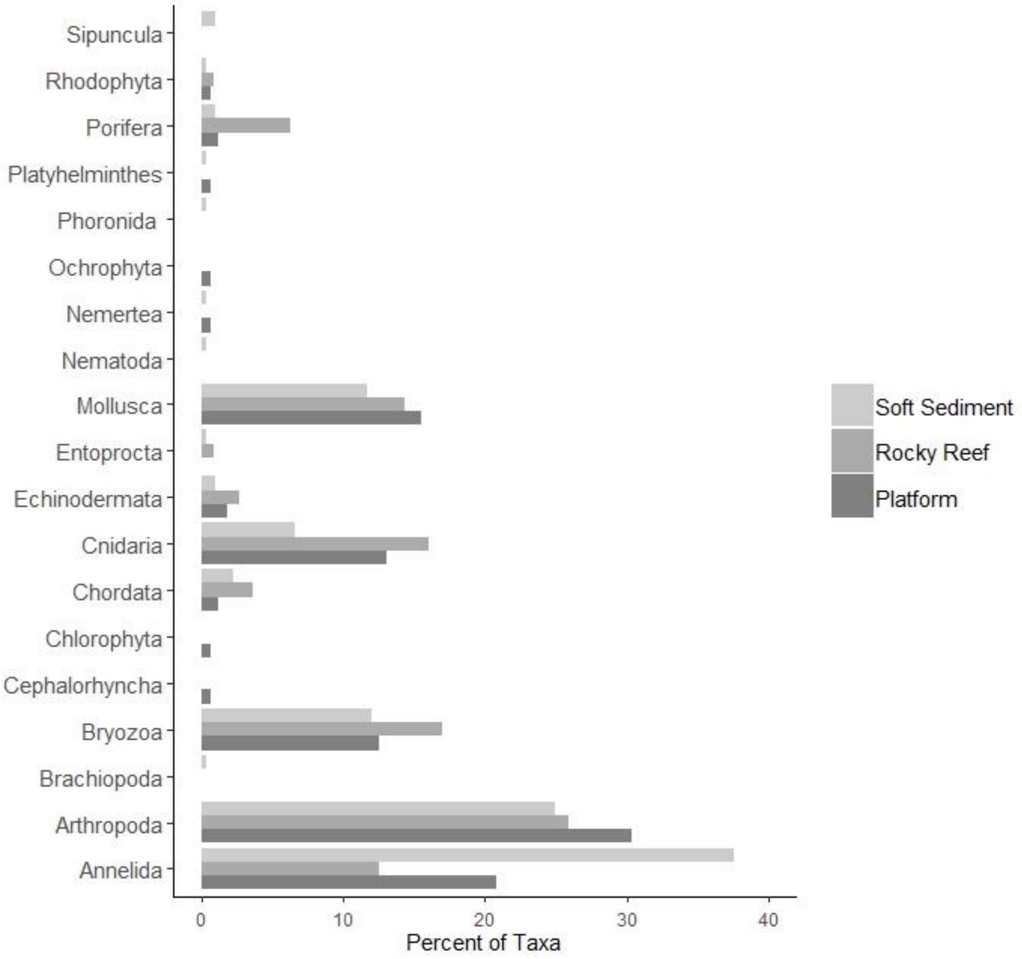

Figure 15 Bar chart showing the percentage of recorded phyla on soft sediment, rock reefs and artificial platforms.

Prior to statistical analysis, data were explored graphically, which highlighted differences in the distribution of taxa amongst the habitat types (soft sediment, rock reef and artificial platforms) and across sites (figure 15). In the first stage, the distribution of recorded phyla at each habitat type was plotted (figure 15). The distribution of Arthropoda, Bryozoa, and Mollusca was relatively even. Taxa that were recorded within these phyla were generally sessile, hard surface colonisers. Annelids were common on both rock reefs and platforms but were most common in sediments and were the dominant phylum at the soft sediment sites (figure 15). In addition, Chordata and Porifera showed greater presence on rock reefs, although relatively few taxa from these phyla were recorded on each substrate.

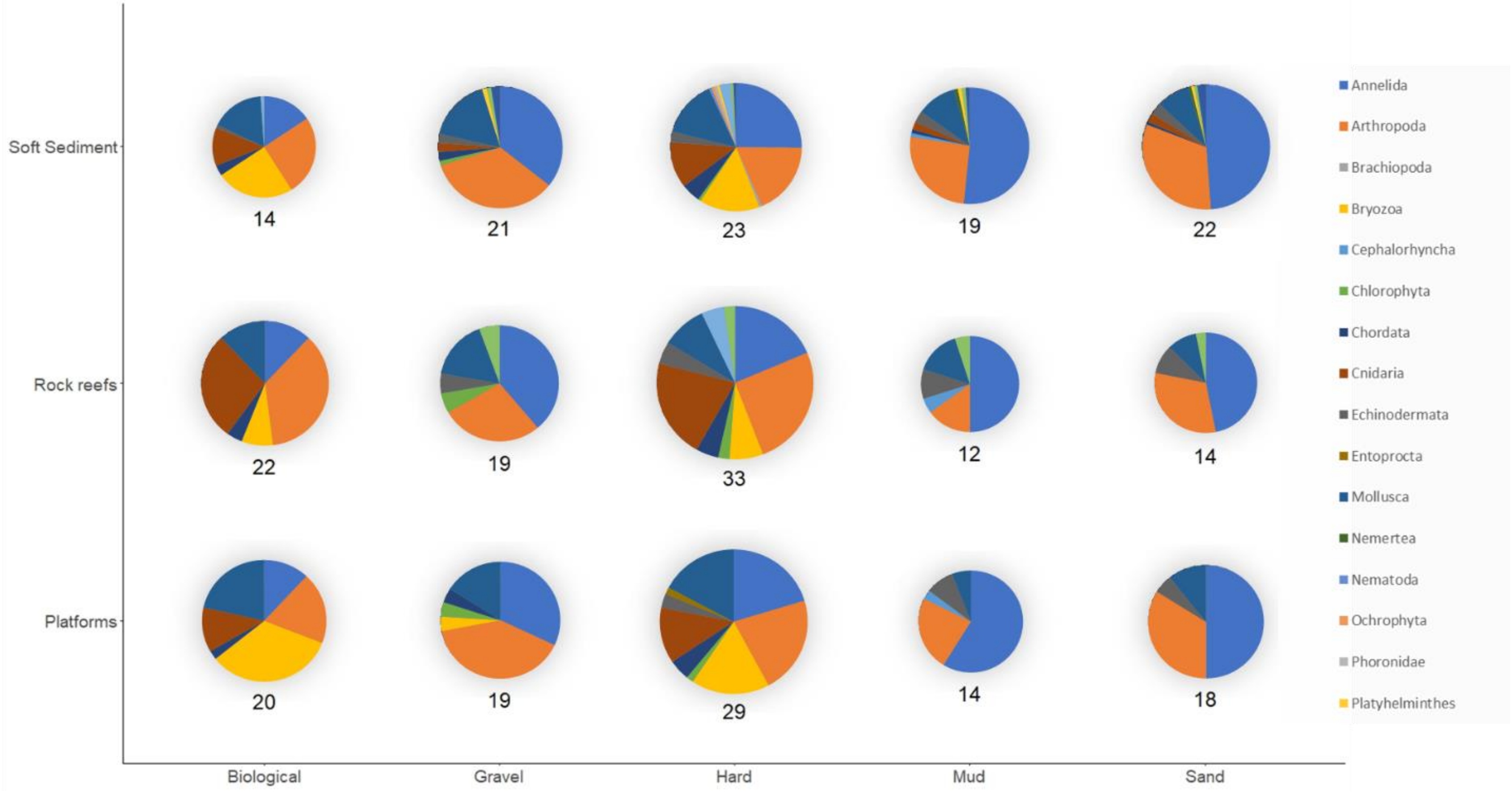

Figure 16 Pie bubble plot showing the % (size of each pie chart and corresponding number underneath) of taxa with an affinity for a given substrate (biological = biota generated substrate (e.g. shells) or another organism (e.g. macroalgae), gravel = mobile rock substrate <256 mm in diameter, hard = non-mobile rock substrate or artificial structures, mud = very fine substrate <63 µm in diameter, sand = fine or coarse substrate 63 µm – 1 mm in diameter) at each site. The slices of the pie charts represent proportion of the phyla corresponding with each site and substrate combination.

A bubble plot was produced to visualise substrate affinities of taxa recorded at each habitat based on published data (figure 16). Whether taxa had an affinity for any given substrate was determined from published literature, species identification guides (Hayward and Ryland, 2017; Young et al., 2002), online databases (Marine life information network ltd, 2018; Worms Editorial Board, 2018), and personal correspondence with experts. Taxa with an affinity for hard substrate dominated all substrate types (29% on platforms, 33% on rock reefs and 23% on soft sediments) as highlighted in figure 16. Taxa substrate affinities were similar between rock reefs and platforms. Both habitat types saw a large drop in taxa affinities for other substrate types. Biological substrate, which included any surface or structure generated by fauna or flora, (e.g. shells, carapaces, algal fronds and encrusting species) was the second most dominant in terms of taxa substrate affinity for platforms and rock reefs (20% and 22% respectively).

There were relatively few taxa recorded on platforms and natural reefs that show an affinity for soft substrate. Taxa with an affinity for mud accounted for 12% on rock reefs and 14% on platforms, and taxa with an affinity for sand accounted for 18% on rock reefs and 14% on platforms, whilst taxa with an affinity for gravel accounted for 19% of both rock reefs and platforms. Conversely, substrate affinities for taxa recorded in soft substrate habitats were relatively even, where 22%, 21% and 19% of taxa had an affinity for sand, gravel and mud in respectively.

Figure 16 also shows that mud and sand substrates were dominated by annelids, with arthropods the next largest group, whereas gravel was dominated by annelids and bryozoans. Colonisation of hard and biological substrata appeared more even between several phyla, including annelids, arthropods, bryozoans, cnidarians and molluscs.

Differences in benthic communities between sites are illustrated in the following heatmaps (figure 17a-g). It is notable that a greater number of taxa were recorded at the soft sediment sites, however relatively few occurred in >50% of samples. Of those that did occur in >50% of samples, *Glycera* spp. were found at all soft sediment sites (figure 17e). Taxa in the class Echinoidea (figure 17f) and family Lumbrineridae (figure 17d) were found at S1 and S2. Whereas taxa in the phylum Nemertea (figure 17c) and the infraclass Euheterodonta (figure 17e) were found at S2 and S3. The polychaete *Ophelia borealis* (figure 17c) dominated S3, occurring in 70% of samples.

Fewer taxa were found at sites R2 and P5 than at the soft sediment sites, however they had a greater number of recorded taxa than the remaining rock reefs and platforms. Again, most taxa occurred in fewer than 50% of samples. However, there were a number of taxa that occurred more frequently. For instance *Obelia* spp. (figure 17c) and Asteroidea (figure 17g) occurred in 67% and 85% of samples from R2 respectively, and 100% of samples from P5. There were several other taxa that occurred in 100% of samples from P5, including those in the class Echinoidea. Whilst the most dominant taxa from R2 were Tubulariidae (figure 17a), found in 91% of samples, and *Diadumene cincta* and *Diplosoma listerianum* (figure 17f), both found in 95% of samples.

Several taxa were particularly prevalent on the artificial structures compared to the other sites. For example, *Jassa* spp (figure 17d) were recorded on all platforms in >65% of samples and <20% of samples from all other sites. The plumose anemone *Metridium* spp. was also frequently observed on all platforms, as well as R1. *Metridium* spp. (figure 17d) occurred in <10% of samples at R2. *Mytilus edulis* (figure 17c) was relatively common on all platforms, although it occurred in less samples from P5 (33%). *M. edulis* was also found in <10% of samples from R1, S1 and S2, and was absent from R2 and S3.

The bryozoan *Electra pilosa* (figure 17f) occurred in approximately 60-80% of samples from energy platforms, as well as 73% of samples from R1 and 47% of samples from R2. *E. pilosa* occurred in ≤26% of samples from soft sediment sites and was absent from P1.

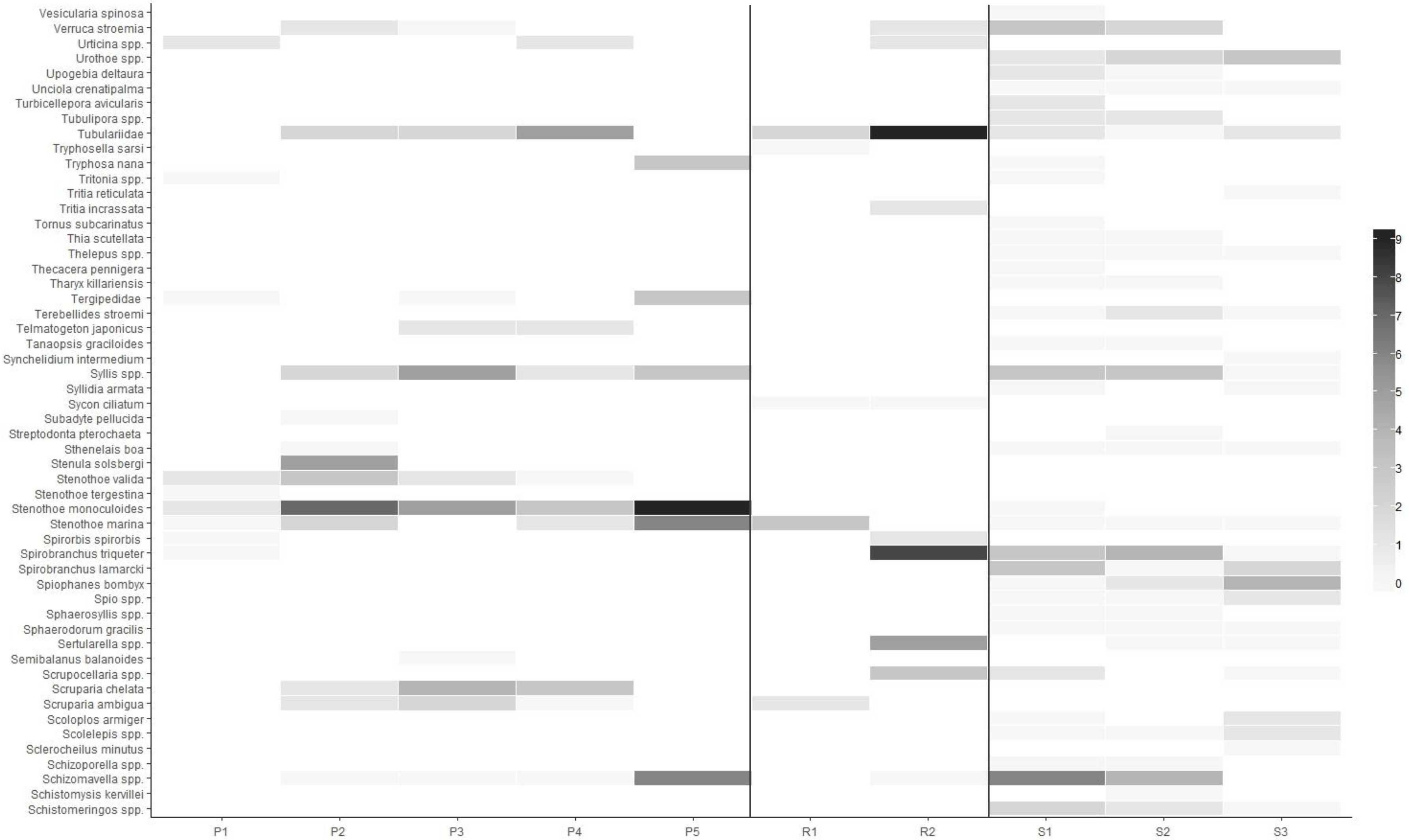

Figure 17a Heatmap showing relative frequency of taxa at each site. Species are ranked as follows: 0 = < 10, 1 = 10 - 19. 2 = 20 - 29. 9 = >90.

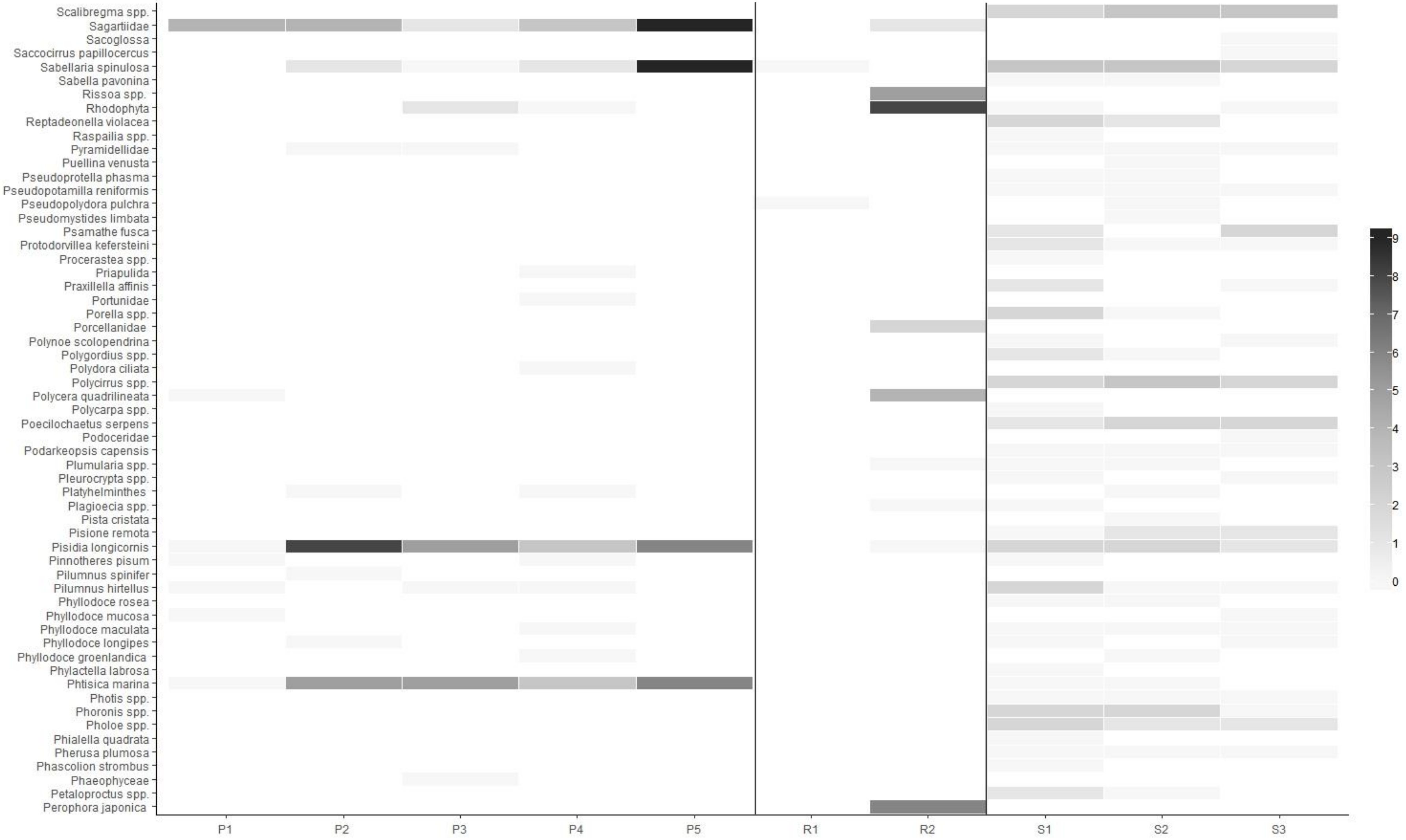

Figure 17b Heatmap showing relative frequency of taxa at each site. Species are ranked as follows: 0 = < 10, 1 = 10 - 19. 2 = 20 - 29. 9 = >90.

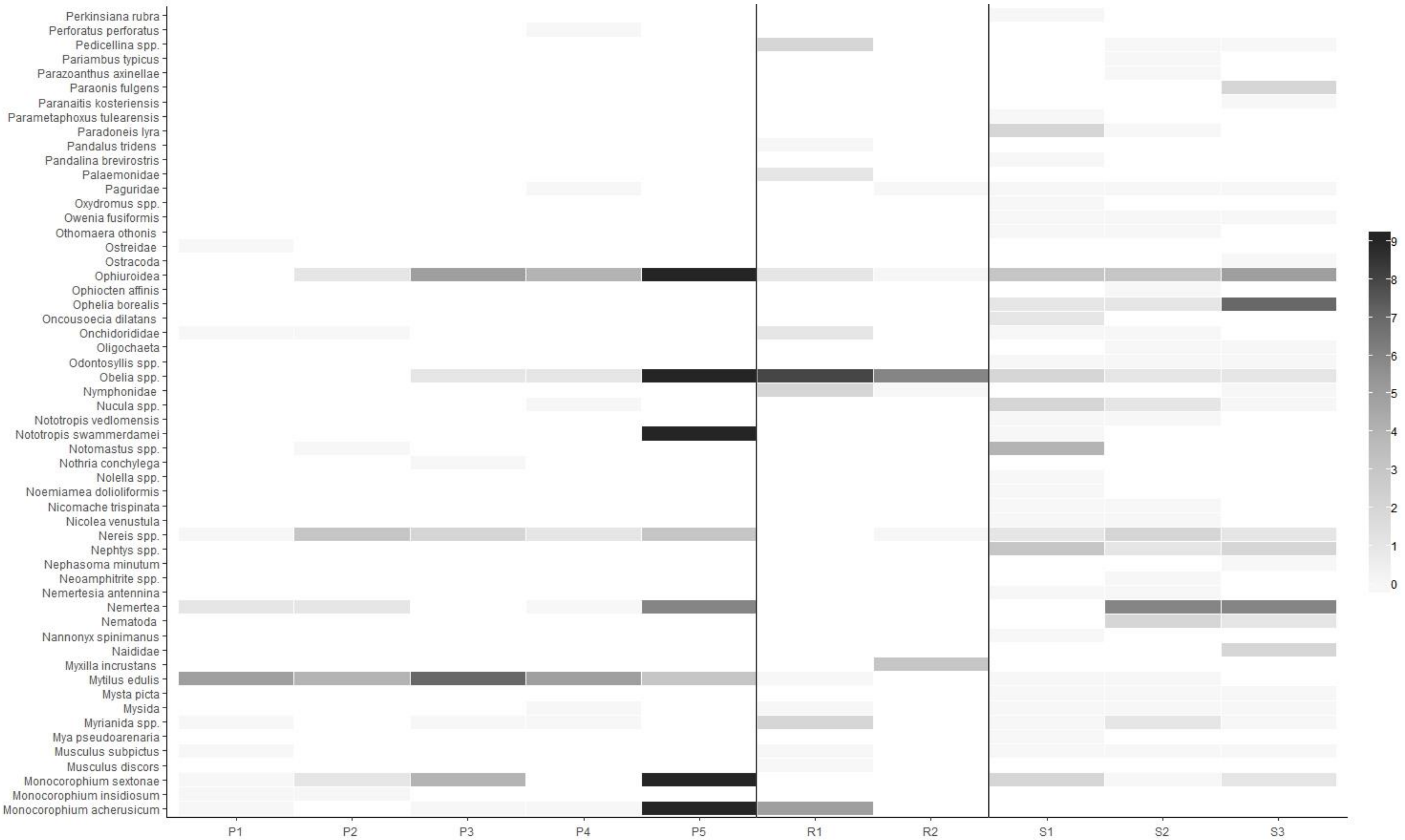

Figure 17c Heatmap showing relative frequency of taxa at each site. Species are ranked as follows: 0 = < 10, 1 = 10 - 19. 2 = 20 - 29. 9 = >90.

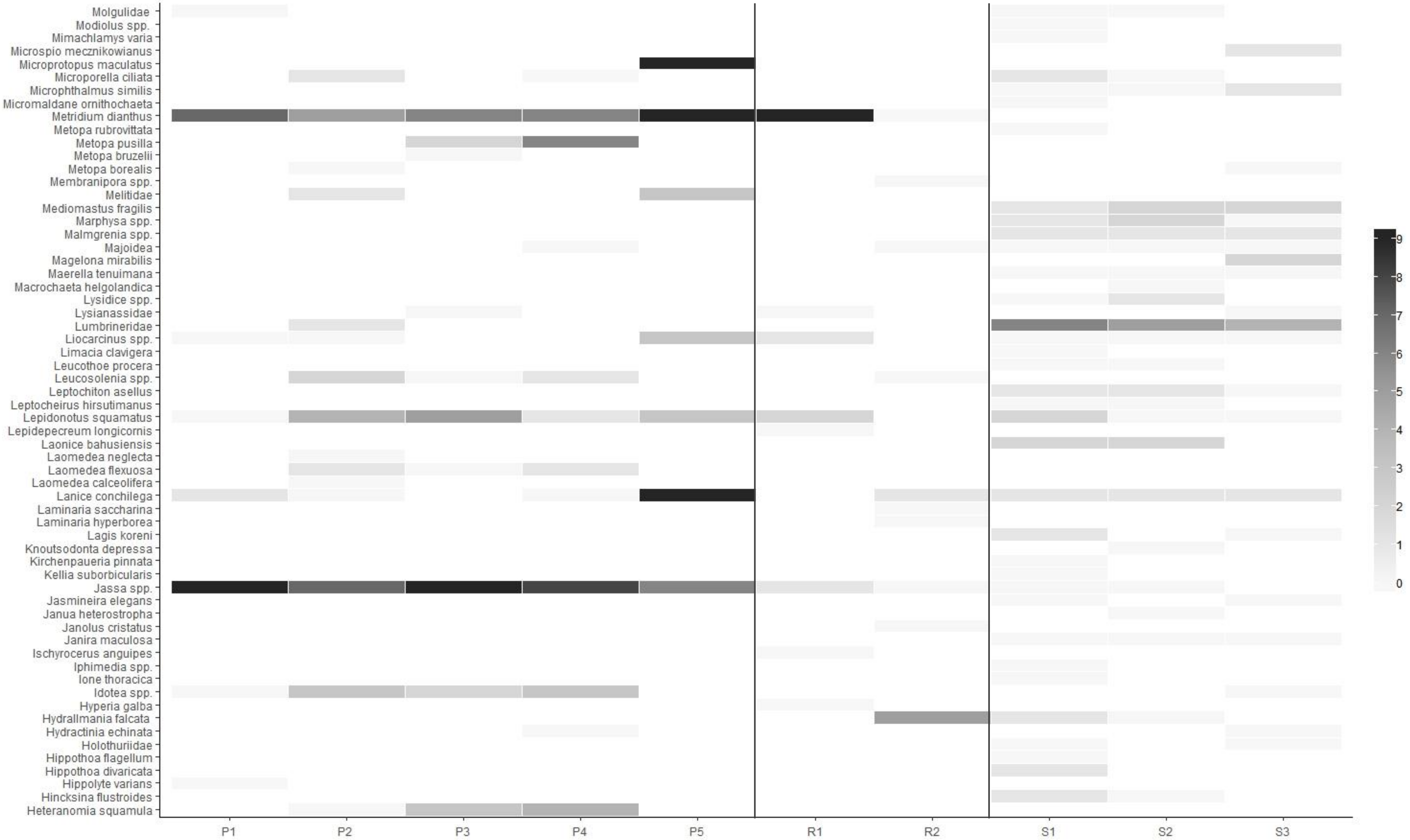

Figure 17d Heatmap showing relative frequency of taxa at each site. Species are ranked as follows: 0 = < 10, 1 = 10 - 19. 2 = 20 - 29. 9 = >90.

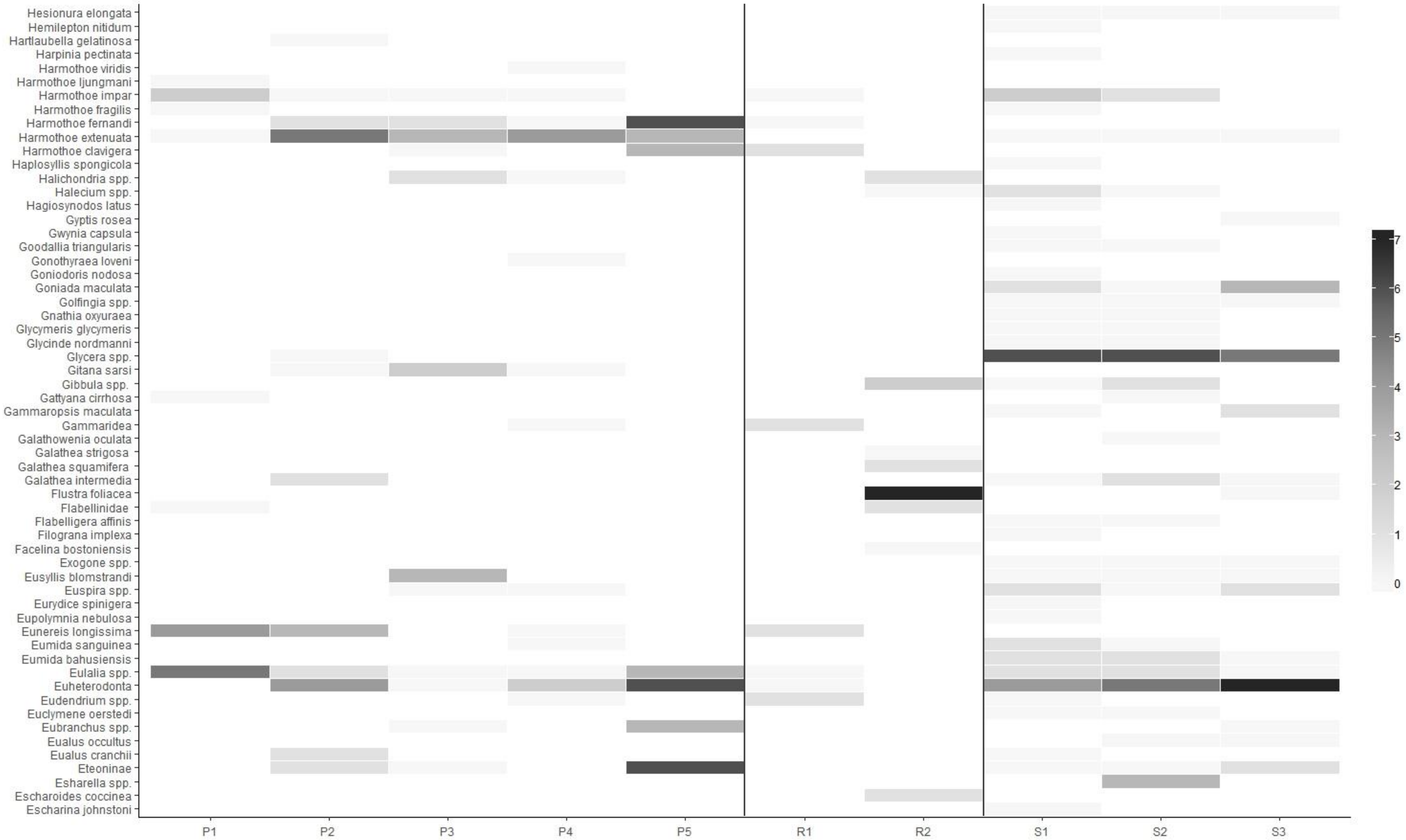

Figure 17e Heatmap showing relative frequency of taxa at each site. Species are ranked as follows: 0 = < 10, 1 = 10 - 19. 2 = 20 - 29. 9 = >90.

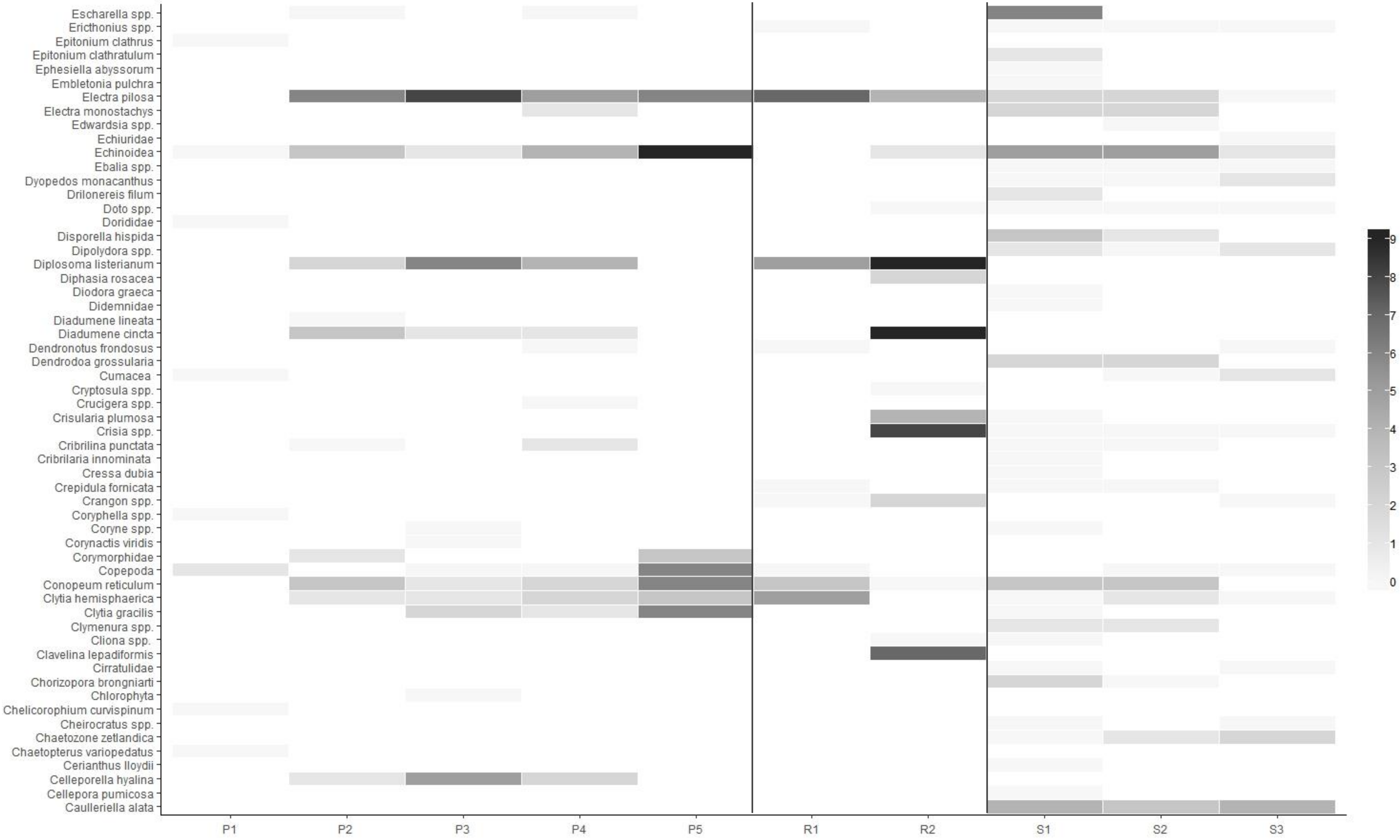

Figure 17f Heatmap showing relative frequency of taxa at each site. Species are ranked as follows: 0 = < 10, 1 = 10 - 19. 2 = 20 - 29. 9 = >90.

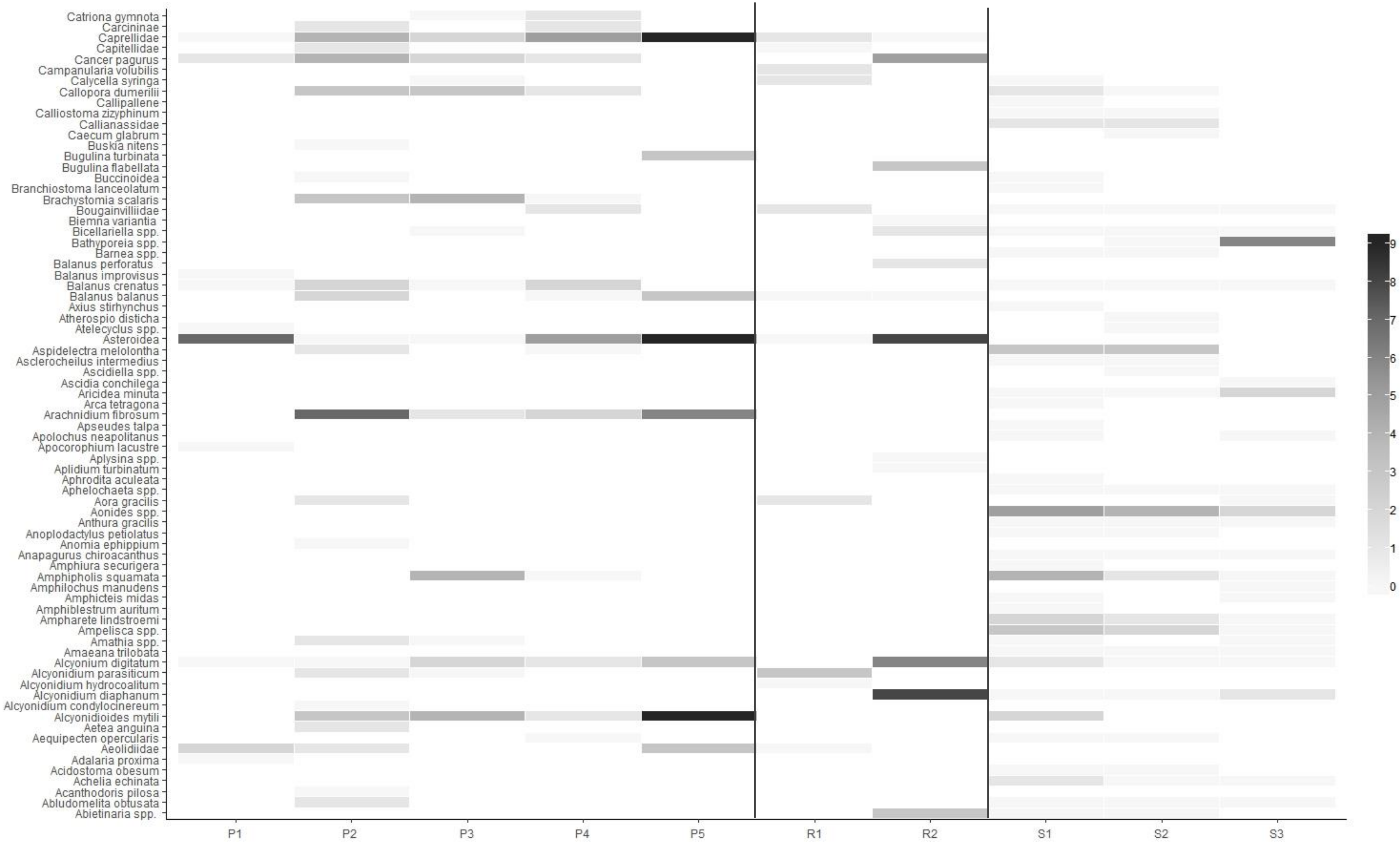

Figure 17g Heatmap showing relative frequency of taxa at each site. Species are ranked as follows: 0 = < 10, 1 = 10 - 19. 2 = 20 - 29. 9 = >90.

3.3.2 Multivariate analysis

For NMS, as the number of dimensions in ordination space increase the stress decreases (Gardener, 2014), however the interpretation of the results becomes more complex. Selecting the appropriate number of dimensions involves performing ordinations whilst gradually increasing the number of dimensions to compare the improvement of the stress. The standard approach aims to obtain a balance between complexity and confidence in the results based on the stress.

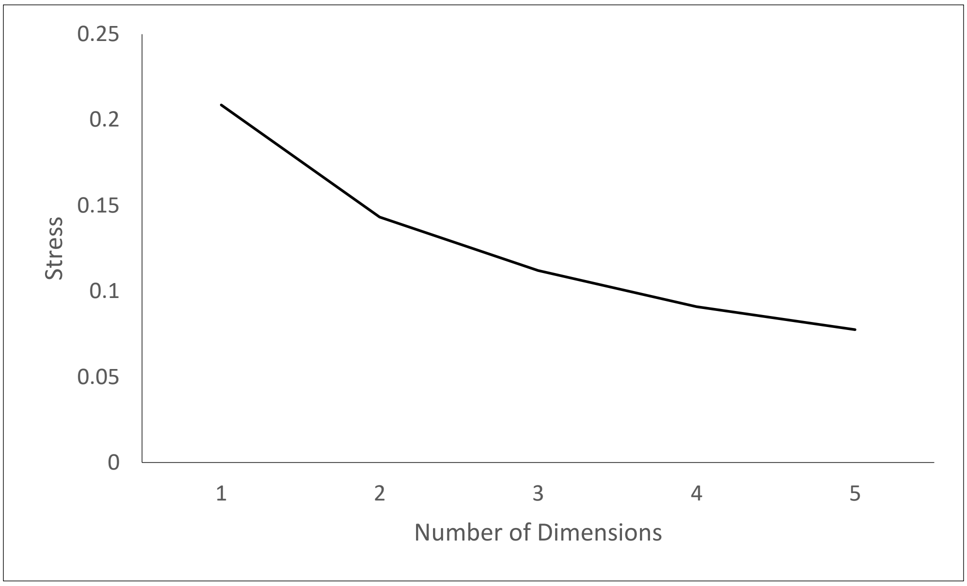

Figure 18 Stress plot for the rock reef and platforms NMS analysis (produced in Microsoft excel).

Figure 18 shows the decrease in stress with increasing dimensions for NMS solutions comparing samples from rock reefs and platforms. The sharp decline in stress from 1-3 dimensions shown indicates a substantial improvement in fit. The shallower decline observed for >3 dimensions suggests that the configurations with more than 3 dimensions show only a small improvement in fit, which wouldn’t justify the added complexity in interpretation. A similar trend was observed for NMS analyses of soft sediment and rock reef samples, and soft sediment and platform samples. A stress of 0.14 provides a reasonable fit, and a 2-dimensional solution would offer low complexity in interpretation. However, in the 2-dimensional case the NMS analyses did not converge to a stable solution. For this reason, a 3-dimension solution was selected for each NMS analysis.

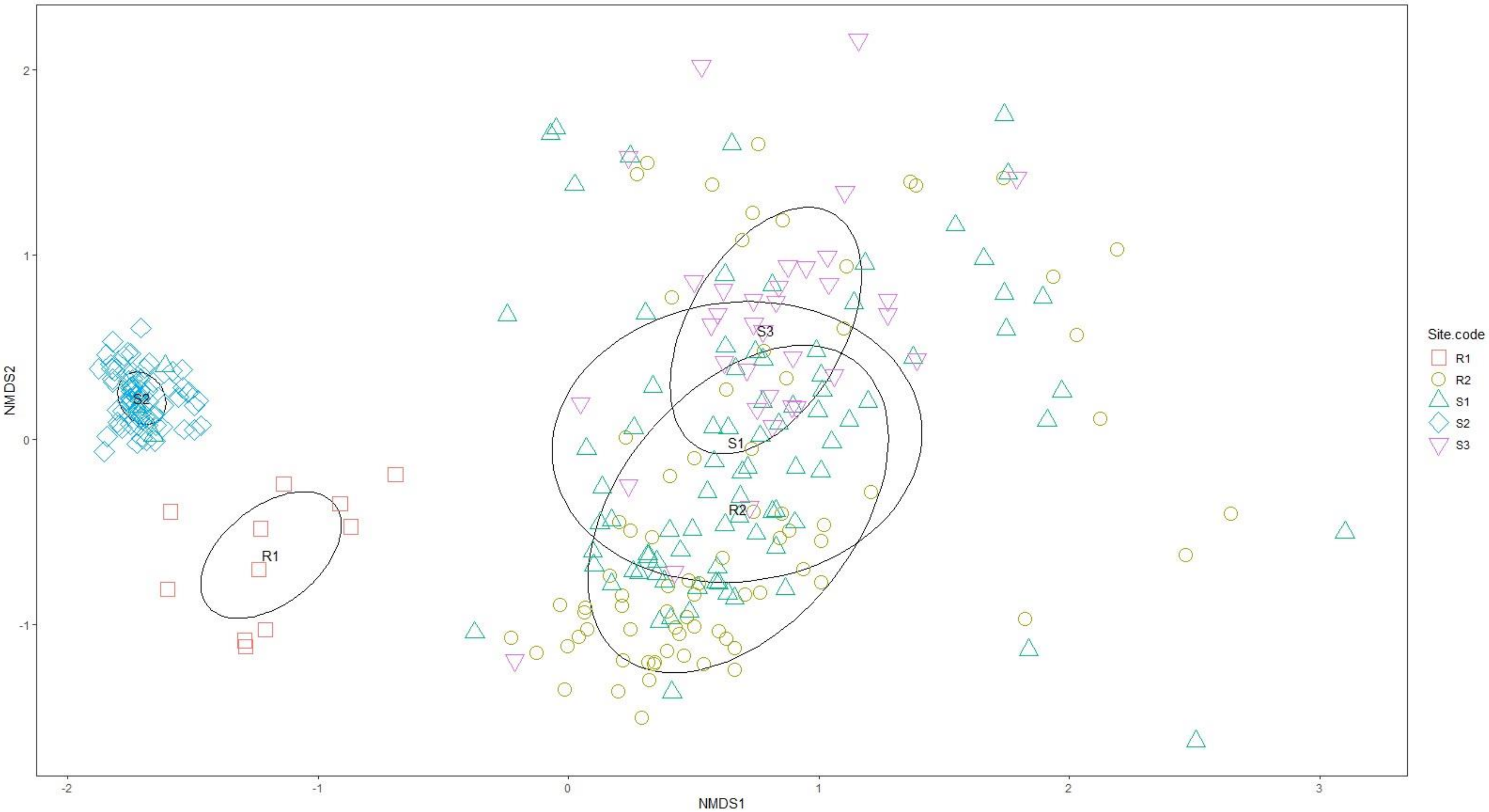

Figure 19 NMS ordination plot (axis 1 and 2) illustrating differences based on β-diversity between soft sediment (S) and rock reef (R) sites. This plot was produced in R with the ggplot2 package. Points represent samples with coloured shapes differentiating the sites samples were taken from.

The NMS solution for soft sediment and rock reef sites had a stress of 0.15, which indicated a reasonable fit of the model to assess β-diversity between sites R1-2 and S1-3. The results show considerable overlap between R2, S1 and S3 (figure 19 and figure 20). There was also greater separation between R1 and R2 than between R2 and S1, and R2 and S3. However, S2 did not overlap with R1 or R2 along either axis 1 and 2, or axis 1 and 3. Thus, the results indicate a difference in community structure, based on β-diversity, between R1 and R2. Moreover, R2 is more similar to S1 and S3 than to R1.

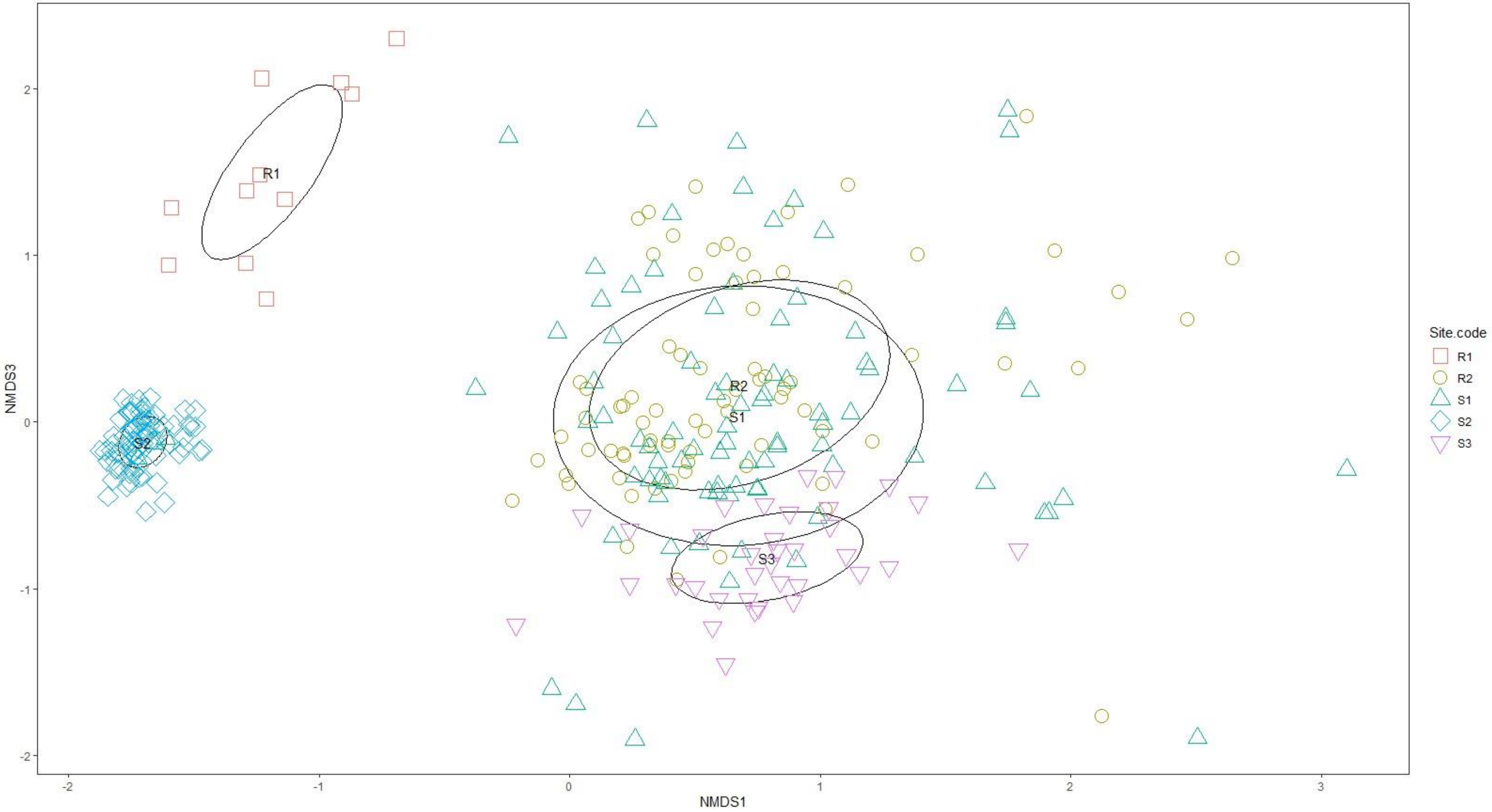

Figure 20 NMS ordination plot (axis 1 and 3) illustrating differences based on β-diversity between soft sediment (S) and rock reef (R) sites. This plot was produced in R with the ggplot2 package. Points represent samples with coloured shapes differentiating the sites samples were taken from.

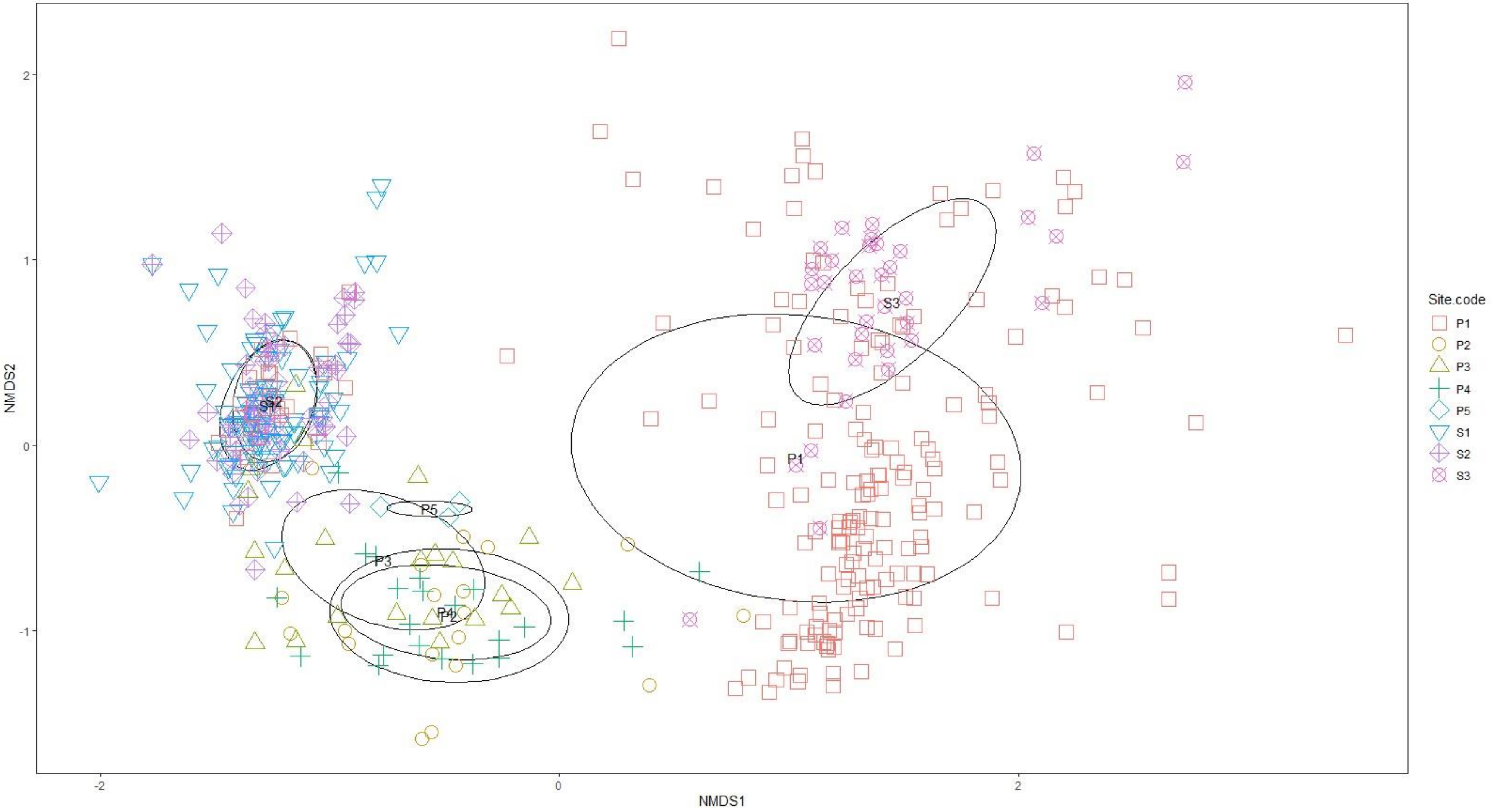

Figure 21 NMS ordination plot (axis 1 and 2) illustrating differences in β-diversity between soft sediment (S) sites and artificial platforms (P). This plot was produced in R with the ggplot2 package. Points represent samples with coloured shapes differentiating the sites samples were taken from.

The NMS solution for soft sediment sites and artificial platforms had a stress of 0.14, indicating a reasonable fit of the model to assess β-diversity between sites P1-5 and S1-3. Figure 21 and figure 22 show sites S1 and S2 heavily overlap, suggesting they had a similar community composition. There is also some overlap between the S1 and S2, and P1-4, and between S3 and P1, P2 and P4. Whereas S1 and S2 are plotted further apart. These results suggest that community composition at S1, S2 and S3 shared greater similarity with communities at P1-4 than S1 and S2 do with communities at S3.

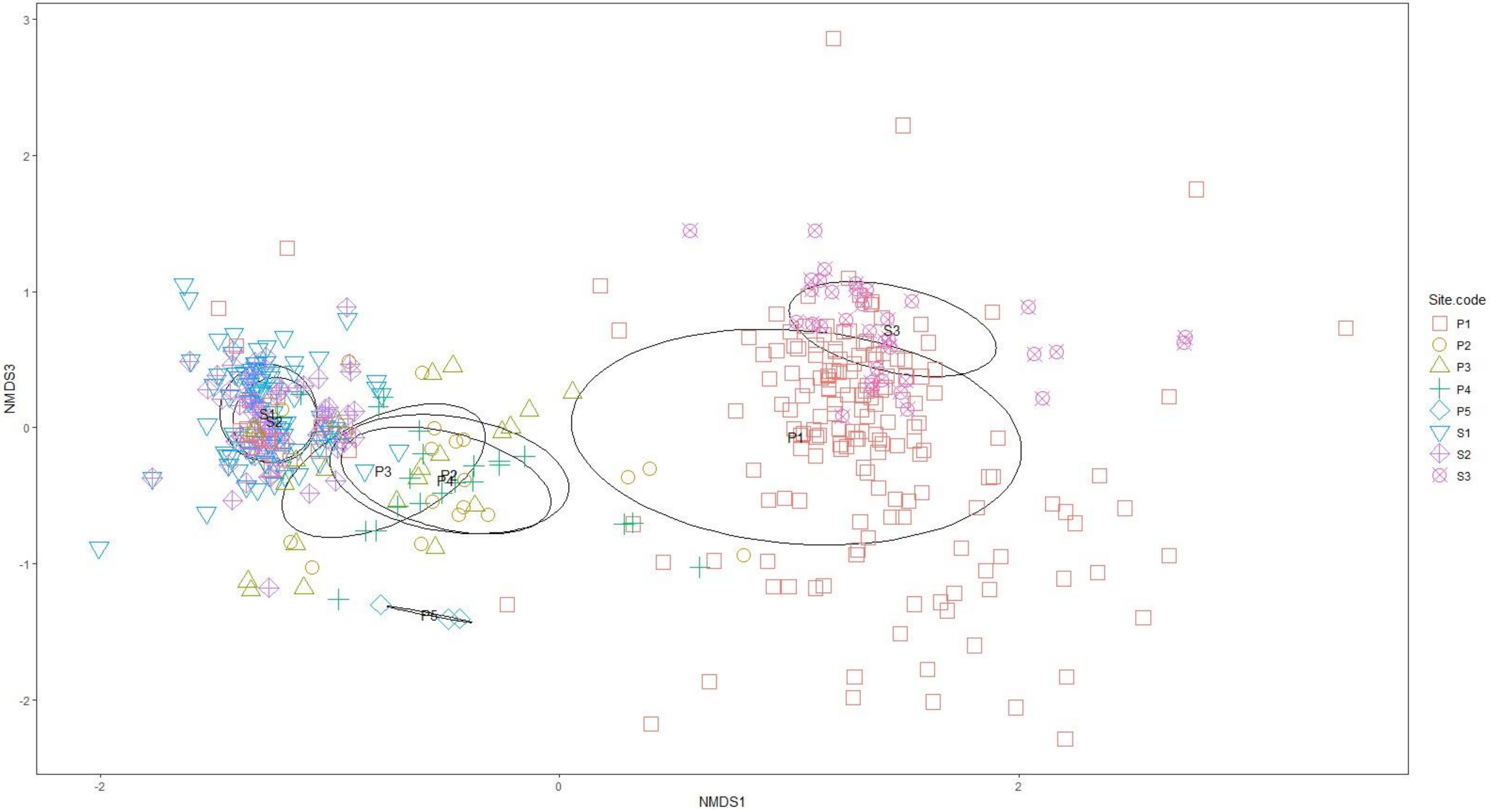

Figure 22 NMS ordination plot (axis 1 and 3) illustrating differences in β-diversity between soft sediment sites (S) and artificial platforms (P). This plot was produced in R with the ggplot2 package. Points represent samples with coloured shapes differentiating the sites samples were taken from.

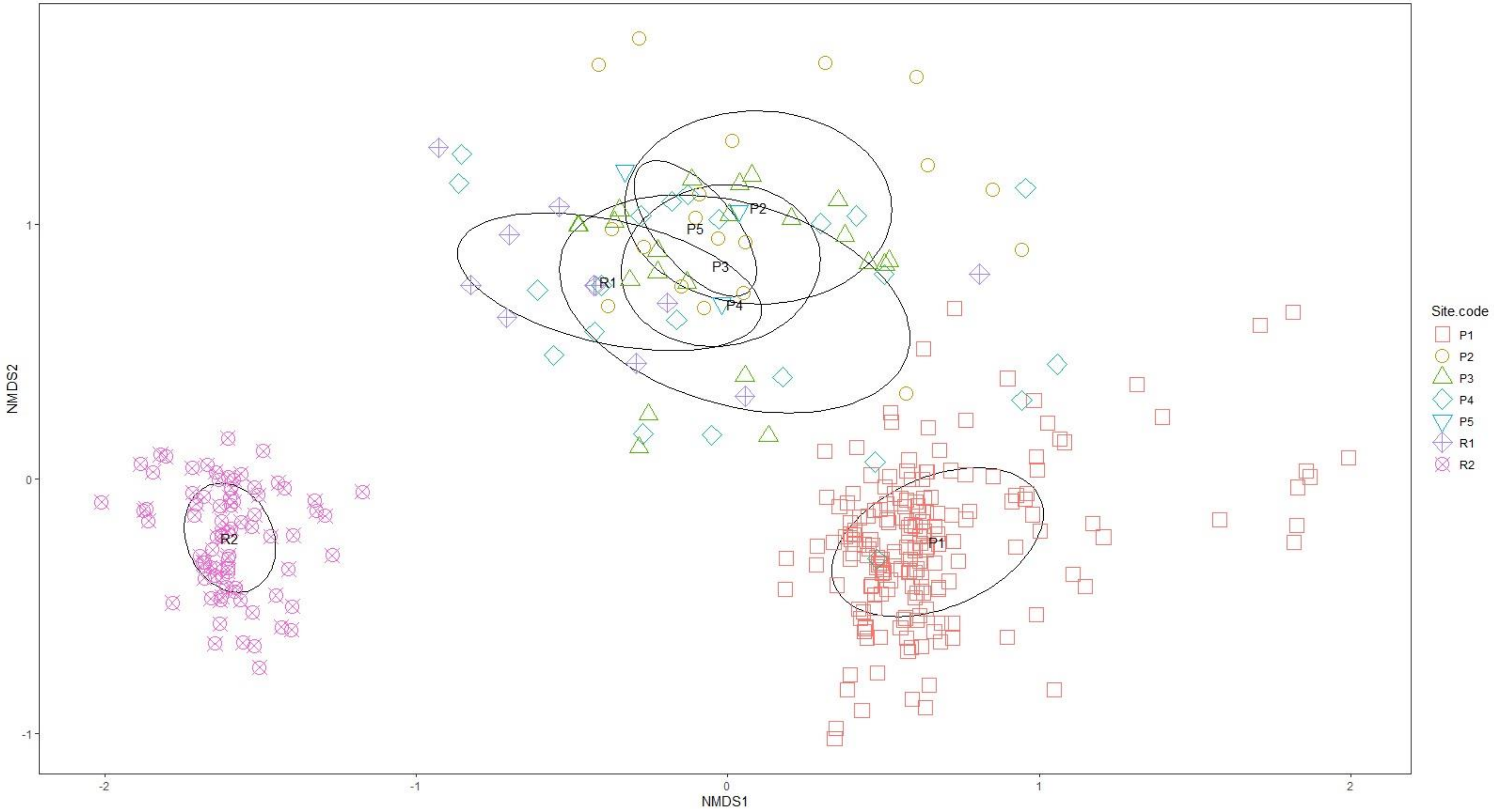

Figure 23 NMS ordination plot (axis 1 and 2) illustrating differences in β-diversity between artificial platforms (P) and rock reef sites (R). This plot was produced in R with the ggplot2 package. Points represent samples with coloured shapes differentiating the sites samples were taken from.

The NMS solution for soft sediment sites and artificial platforms had a stress of 0.12, indicating a reasonable fit of the model to assess β-diversity between sites P1-5 and R1-2. Hence, the results of the NMS show that there was a difference in community structure, based on β-diversity, between the natural reefs and the artificial platforms. Viewing the ordination plot along axes 1 and 2 (figure 23) it is evident that samples from R1 and the energy platforms P2-5 were grouped close together, indicating similar community compositions between those sites.

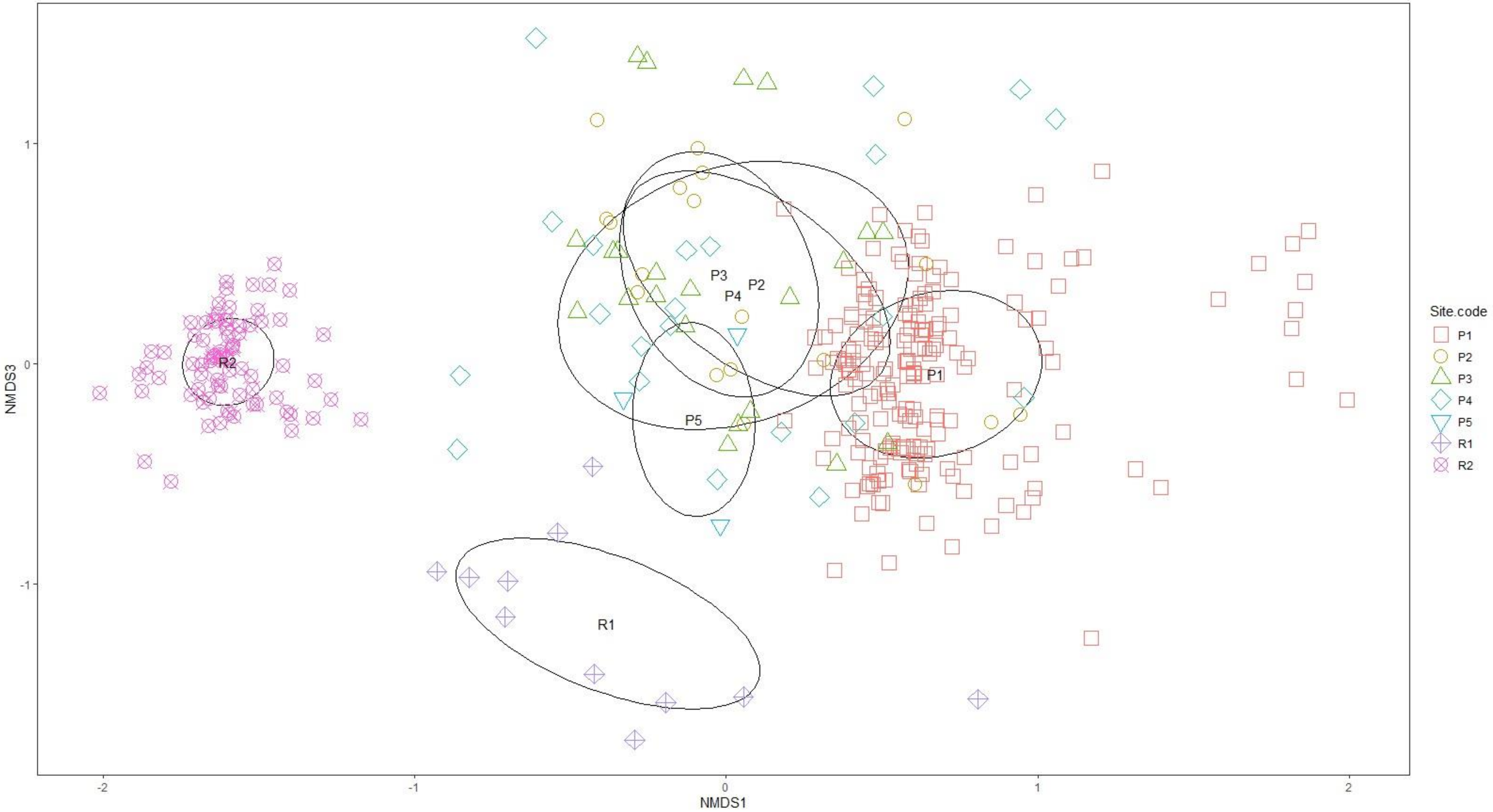

Figure 24 NMS ordination plot (axis 1 and 3) illustrating differences in β-diversity between rock reef (R) sites and artificial platforms (P). This plot was produced in R with the ggplot2 package. Points represent samples and the shapes of the points differentiate the sites samples were taken from.

Axes 1 and 3 (figure 24) also show the energy platforms grouped together but highlight a greater separation between the platforms and R1. Samples from R2 are clustered tightly together with the greatest separation from other sites. Thus, the ordination suggests that, whilst there is a difference in community structure, based on β-diversity, between the natural and artificial sites, the community composition between R1 and the platforms are more similar than between R2 and the platforms.

Samples from P1 appear loosely clustered, although there is some overlap with samples from the platforms along axes 1 and 2, and 1 and 3. There is also overlap between P1 and R1 along axes 1 and 2. This suggests communities at P1 were more similar to those at the other platforms than at the natural reefs. However, communities at P1 were more similar to those at R1 than R2.

Permutational multivariate analysis of variance was performed to test the hypothesis that community structure did not differ between sites. Comparing β-diversity across all sites, PERMANOVA (table 4) indicated that differences were significant ($P < 0.01$). Although site explained around 21% of the variability ($R^2 = 0.21$) it is likely that some other factor, or several factors, greatly influence diversity between sites.

Table 4 PERMANOVA for differences in β-diversity between sites based on the full data. Significance codes (based on a 95% confidence interval): 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.**

	Degrees of freedom	Sum of squares	R^2	F-statistic	P-value	Significance
Site	9	48.02	0.21	15.76	<0.01	***
Residual	534	180.80	0.79			
Total	543	228.82	1			

Table 5 showed that depth and distance from shore had a significant effect on β-diversity ($P < 0.01$), although these factors explained little of the variance. Depth explained around 1% of the variance ($R^2 = 0.012$) and distance from shore explained around <1% of the variance ($R^2 = 0.004$). The interaction between substrate type and depth had a highly significant effect of community structure ($P < 0.01$). Whereas the interaction between depth and distance from shore had a weekly significant effect on community structure ($P \cong 0.05$).

Table 5 PERMANOVA for differences in β-diversity from reduced data for which depth, distance from shore and substrate type were available. Significance codes (based on a 95% confidence interval): 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.**

	Degrees of freedom	Sum of squares	R^2	F-statistic	P-value	Significance
Site	8	51.22	0.30	23.15	<0.01	***
Depth	1	2.19	0.01	7.90	<0.01	***
Distance	1	0.64	<0.01	2.31	<0.01	**
Substrate	1	0.22	<0.01	0.79	0.73	
Depth:Substrate	2	1.36	0.01	2.46	<0.01	***
Residual	411	113.70	0.67			
Total	424	169.31	1			

Pairwise contrasts (table 6) showed that differences in community structure were generally significant between the individual sites (P <0.05). Community structure was not shown to be significantly different between platforms P5 and P2 (P = 0.14), and P5 and P4 (P = 0.37). Neither was P5 significantly different from natural sites R1 (P = 0.12), R2 (P = 1.00), S1 (P = 1.00), and S2 (P = 0.11). Further, there was no significant difference in community composition between sites S2 and S3 (P = 0.06).

Whilst the PERMANOVA gave statistically significant results it is important to note that R^2 values are generally low indicating that other habitat characteristics are also important in structuring communities.

Table 6 PERMANOVA pairwise contrasts for differences in β-diversity between sites (based on Jaccard biodiversity index). Significance codes (based on a 95% confidence interval): 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.**

Pairs	F-Statistic	R^2	P-value	Significance
R1 vs R2	13.20	0.13	<0.01	**
R1 vs P2	5.86	0.17	<0.01	**
R1 vs P5	3.62	0.23	0.12	
R1 vs P4	4.72	0.13	<0.01	**
R1 vs S1	15.26	0.13	<0.01	**
R1 vs S2	5.94	0.07	<0.01	**
R1 vs S3	6.24	0.12	<0.01	**
R1 vs P1	5.63	0.03	<0.01	**
R1 vs P3	7.50	0.19	<0.01	**
R2 vs P2	14.66	0.13	<0.01	**
R2 vs P5	0.56	0.01	1.00	
R2 vs P4	14.37	0.13	<0.01	**
R2 vs S1	9.68	0.06	<0.01	**
R2 vs S2	30.30	0.17	<0.01	**
R2 vs S3	28.96	0.21	<0.01	**
R2 vs P1	42.97	0.14	<0.01	**
R2 vs P3	25.65	0.21	<0.01	**
P2 vs P5	3.22	0.14	0.14	
P2 vs P4	6.28	0.14	<0.01	**
P2 vs S1	17.29	0.14	<0.01	**
P2 vs S2	9.21	0.09	<0.01	**
P2 vs S3	10.32	0.17	<0.01	**
P2 vs P1	8.89	0.04	<0.01	**
P2 vs P3	11.91	0.23	<0.01	**
P5 vs P4	2.43	0.10	0.37	
P5 vs S1	0.99	0.01	1.00	
P5 vs S2	2.63	0.03	0.11	
P5 vs S3	3.47	0.09	0.01	*
P5 vs P1	2.90	0.02	<0.01	*
P5 vs P3	4.34	0.16	0.02	.
P4 vs S1	18.76	0.15	<0.01	**
P4 vs S2	4.23	0.04	<0.01	**
P4 vs S3	4.37	0.07	<0.01	**
P4 vs P1	5.56	0.03	<0.01	**
P4 vs P3	2.18	0.05	0.14	
S1 vs S2	37.73	0.19	<0.01	**
S1 vs S3	36.37	0.23	<0.01	**
S1 vs P1	53.41	0.16	<0.01	**
S1 vs P3	32.41	0.23	<0.01	**

S2 vs S3	2.16	0.02	0.06	
S2 vs P1	13.51	0.05	<0.01	**
S2 vs P3	6.64	0.07	<0.01	**
S3 vs P1	8.37	0.04	<0.01	**
S3 vs P3	5.40	0.09	<0.01	**
P1 vs P3	9.75	0.04	<0.01	**

Table 7 shows the pairwise contrasts between substrate types rock, steel (the platform members) and soft sediment. We can see that there was a highly significant difference in community composition (*P* < 0.001) between rock and steel, rock and soft sediments and steel and soft sediments. Although these pairings explained little of the variation.

Table 7 PERMANOVA pairwise contrasts for differences in β-diversity between substrate types (rock, steel and soft sediments) (based on Jaccard biodiversity index). Significance codes (based on a 95% confidence interval): 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.**

Pairs	F-statistic	R^2	P-value	Significance
Rock vs Steel	38.84	0.10	<0.01	***
Rock vs Soft Sediment	12.83	0.07	<0.01	***
Steel vs Soft Sediment	28.27	0.08	<0.01	***

The NMS and PERMANOVA are non-parametric analyses that provide a robust means of assessing multivariate community data. Overall the results of these analyses suggest that community composition between sites was significantly different, at the 95% confidence interval. However, there is evidence that differences in community structure are not based on location and substrate type alone, but that other factors such as depth and distance from shore play a role in structuring the community (table 5).

3.4 Discussion

There is growing awareness of the potential for OWFs to modify marine ecosystems across multiple scales (Causon and Gill, 2018; Coates et al., 2014; Krone et al., 2013a, 2013b). As commitment and investment in offshore wind is expected to continue to grow there is a need to understand consequences to the marine environment and whether the colonising communities on the multiple artificial structures will change the ecosystem where they are installed and determine how these changes are manifest.

3.4.1 Community structure on artificial and natural substrates

The results of this study demonstrate differences in epibenthic communities between artificial structures, natural rock reefs and soft sediments in the southern North Sea. The soft sediment sites had the greatest mean number of taxa. However, few taxa were found in samples with high frequency (figure 17a-g). Polychaetes, particularly bristleworms (*Ophelia borealis*) bloodworms (*Glycera* spp) and lumbrinerids, were found in the majority of samples. Euheterodonta were also common at sites S1-3, as were ribbon worms (*Nemertea*) at sites S2 and S3.

The mean number of taxa at the platforms was slightly greater than at natural reefs (0.8 and 0.6 respectively). As with the soft sediment sites, few taxa occurred with high frequency in samples from platforms P1-4, and the reef R1 (figure 17a-g). This finding supports that of Kerckhof et al (2010) who reported that communities on gravity based concrete offshore wind turbine foundations on the Thornton Bank, in the southern North Sea were dominated by a limited number of species. Sessile invertebrates, such as the colonial bryozoan *E. pilosa*, and the anemone *M. dianthus*, were dominant taxa on both platforms and rock reefs. Whereas *Jassa* spp. were dominant on platforms alone.

Community structure between the platforms and soft sediments in the southern North Sea were shown to be significantly different. In addition, community composition was significantly different between the rock reefs and platforms P1-4. This finding is in line with several studies that have shown epifauna assemblages found on artificial structures differed from those on nearby reefs and natural substrate (Bulleri, 2005; Bulleri and Chapman, 2004; Connell, 2001; Connell and Glasby, 1999). Yet, differences between R1 and P5, and R2 and P5 were not significant. Notably, R2 and P5 shared a number of common taxa (occurring in >50% of the samples). It is likely to be an artefact of the sampling effort as all samples from P5 were taken from the scour protection layer at the base of the platform. As such, samples from P5 were taken from a similar depth to R1 (22 and 28 m respectively) and similar distance from shore (41 and 30 km respectively).

Had samples from the jacket structure been available a similar community structure to P1-4 may have been recorded.

The sites included in this study were based on existing and available data. They differed in geographic location, thus they were subject to different conditions that are likely to have influenced the results. For example, current regimes differed between the areas. On the Dutch continental shelf, where R1 and P2-5 were located (figure 12), the prevailing currents are north easterly and easterly (Houbolt, 1968; Lee and Ramster, 1968). In Outer Thames Estuary, the location of S1-3, the prevailing current is predominantly southerly, with south-westerly and north-easterly flood and ebb tides respectively (Gardline Geosurvey Ltd., 2012, 2007; Royal Haskoning, 2016). The German Bight, on the other hand, the location of P1 and R2, is a highly dynamic region where river plume, thermal and upwelling fronts, and a complicated structure of eddies, has been reported (Becker et al., 1992, 1983; Franz and Klein, 1986).

The PERMANOVAs indicated that differences in site explained most of the variability in community structure (table 5). Further, significant differences in community composition occurred between sites of the same substrate type, such as between the natural rocky reefs at R1 and R2 (table 7). This supported the observations from the NMS (figure 19, figure 20, figure 23 and figure 24). Although significantly different (table 6), communities at R1 appear more similar to those on the platforms, particularly P2-5, than those at R2 (figure 23 and figure 24). This finding further validates the evidence that communities are structured by variables other than habitat type, such as depth or surface orientation. Such variability can affect habitat conditions influencing available niches for occupancy. Depths at R1 range from 10-40 m (Joschko et al., 2008) and samples collected at R1 were taken from a depth of 28 m. Depths at R2 range from 8-22 m (Kühne and Rachor, 1996) and samples collected from R2 ranged from 9-17 m. However, conclusions should be drawn with caution. The sampling methods employed at R1 and R2 differed. A larger area was sampled from R2, but taxa were identified in situ only. By processing samples from R1 in a laboratory a higher level of accuracy would have been achievable. Had the same methods been applied at both sites the community structures may have been shown to bear closer similarity.

Depth and distance from shore were shown to have a significant effect overall on β-diversity between soft sediment sites, reefs and platforms (table 5). It should be noted that the significant effect of distance from shore may be a product of a increasing average depth with increasing distance from shore in general. Zonation with respect to depth is well documented and has previously been demonstrated for epibenthic communities on oil and gas platforms (Bram et al., 2005; Forteath et al., 1982). This is in line with the finding of Coolen (2017) who showed that species richness varied with depth on platforms P1-5 and at R1. Also, Van Der Stap et al (2016) demonstrated differences in epibenthic colonisation on structures on the Dutch continental shelf along a depth and age gradient. They found that on the platform with the youngest community age (3 years) *Mytilus edulis* was dominant and suggested that it was an early coloniser of offshore platforms. Similar patterns have been seen at OWF sites, where *M. edulis* was shown to dominate fouling communities within the first two years of operation (Krone et al., 2013b). Coolen (2017) also found that spatial orientation had a significant effect on community structure, with increased species richness on vertical surfaces compared to horizontal. Spatial orientation has been described as a determinant of habitat heterogeneity, spatial and temporal variability in the habitat features (Dean and Connell, 1987a, 1987b; Geesey et al., 1996; Moura et al., 2008; Stephenson and Stephenson, 1949). Habitat heterogeneity is related to species richness (Connor, 1991).

Substrate type was not shown to have an overall significant effect on β-diversity, however the interaction between depth and substrate type was found to have a significant effect on β-diversity. Pairwise comparisons (table 7) found that there was a significant difference between rock and steel substrate, rock and soft sediment substrate and steel and soft sediment substrate are likely to be associated with differences in substrate depth.

3.4.2 Conclusions

Investment in offshore wind energy will continue in the near future, with projects under construction, in the pre-construction phase or consented producing almost double the current installed capacity once completed. As offshore wind energy continues to expand in the southern North Sea, we can expect potentially significant changes in local and regional biodiversity.

The results present evidence for a change in epibenthic community composition due to the installation of energy structures. Offshore platforms have been colonised by organisms typical of rocky shore habitats that would ordinarily be absent from the offshore environment, such as *M. edulis* and *S. balanoides*. Thus, it is likely that communities colonising offshore wind turbine substructures would differ to a large degree from those found on natural rock reefs and the soft sediments that dominate the seabed in the southern North Sea. However, the data analysed were taken from existing datasets from multiple surveys which were intended for a different purpose to what has been attempted in this study. Due to the differences in metrics recorded (e.g. abundance, biomass, coverage and presence/absence) all data was transformed to presence/absence. Whilst useful, at this course scale of analysis, the ecological information that can be described by the data is limited. Taxa that appear uncommon at the presence/absence level may be highly abundant in a few of the sampled locations. Further, beyond the substrate type the sites differed in geographic location and as a result they differed in topography and oceanographic conditions. Therefore, the results of this study are likely to have been influenced by the differences in location of the study sites.

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Chapter 4: Assessing the Effect of Offshore Energy Structures on Ecosystem Function in the Southern North Sea Using Biological Traits Analysis

4.1 Introduction

Offshore wind energy has shown considerable growth over the last decade and this development is set to continue, with estimates that offshore wind may generate more than 10% of Europe's energy (approximately 140 GW) by 2030 (Langhamer, 2012; Zervos et al., 2009). Although offshore wind farms (OWFs) are expected to benefit global environments through low CO_2 energy production, they have the potential to modify marine ecosystems and change local and regional biodiversity (chapter 3, Causon and Gill, 2018).

Due to engineering constraints, OWFs have generally been installed in regions characterised by soft sandy sediment, such as the Southern North Sea (Hooper et al., 2015; Kerckhof et al., 2011; Lengkeek et al., 2013; Mangi, 2013). As has been seen for oil and gas platforms (Forteath et al., 1982; Mallat et al., 2014; Southgate and Myers, 1985; Wolfson et al., 1979), ship wrecks (Lengkeek et al., 2013; Walker et al., 2007; Zintzen et al., 2008) and coastal defence structures (Hall et al., 2018; Ido and Shimrit, 2015; Moschella et al., 2005), wind turbine foundations provide hard substrate that are rapidly colonised by complex epibenthic communities (Bouma, 2012; Degraer et al., 2010; Kerckhof et al., 2012, 2010, 2009; Krone et al., 2013b; De Mesel et al., 2013). Thus, offshore wind turbines may lead to a local ecological community shift from sediment associated fauna to hard bottom and intertidal species (chapter 3; Causon and Gill, 2018; Kerckhof et al., 2011; Lengkeek et al., 2013; Mangi, 2013). Indeed there is evidence that epifauna assemblages on artificial structures, including wind turbine foundations, differ from those on nearby reefs and natural hard substrate (Connell and Glasby, 1999; Petersen and Malm, 2006).

Analysis of the taxonomic relationship was extended to include soft substrate communities in chapter 3. It was shown that community composition of assemblages found on artificial platforms in the southern North Sea were significantly different from those found in soft sediments and on natural rock reefs. Thus, it is expected that community composition within an OWF would differ from that of the pre-OWF habitat. However, it is not clear whether changes in community composition translate to changes in functional diversity (Bremner et al., 2003; Díaz and Cabido, 2001). The aim of this study was to ascertain whether changes in community composition in benthic systems, following the installation of an OWF, would give rise to functional changes at the ecosystem level. Ecosystem services are, in essence, by-products of ecosystem functioning that benefit human welfare (Liquete et al., 2016). Therefore, understanding how functioning in an ecosystem is affected by community composition may provide insight into the functional resilience of that system, the persistence of ecosystem functions under changing environmental conditions (Walker et al., 1999), and the sustainability of ecosystem services.

Ecosystem functions include processes (e.g. nutrient cycling) and properties (e.g. abundance of component species) in an ecosystem, along with the maintenance of those processes and properties over time (Bremner et al., 2006a; Giller et al., 2004; Reiss et al., 2009). Although it is thought that high biodiversity supports high ecosystem functionality (Balvanera et al., 2006; Cardinale et al., 2012; Gamfeldt et al., 2015; D.U. Hooper et al., 2005; Lefcheck et al., 2015; Loreau et al., 2001), ecosystem functioning depends on traits exhibited by component taxa, regardless of community composition (Bremner et al., 2006a, 2003). For example, in benthic systems, traits such as feeding mode affect a number of processes including nutrient cycling and productivity. Suspension feeders, including *Mytilus edulis*, consume pelagic primary producers, particulate organic matter and microbes from the water column (Bremner, 2008). Dense colonies of *M. edulis* transfer organic nutrients from the water column to the seabed through faecal matter and detritus (Coates et al., 2011, 2014; Köller et al., 2006; Maar et al., 2009). Infaunal deposit feeders and grazers transfer organic matter on the sea bed in to the sediment, influencing the rates of remineralisation and inorganic nutrient efflux (Aller, 1988; Christensen et al., 2000; Hansen and Kristensen, 1997; Kristensen, 2000; Lohrer et al., 2004; Welsh, 2010). *M. edulis* is frequently reported on artificial hard substrate such as buoys (Langhamer et al., 2009), oil and gas platforms (Guerin et al., 2007; Hubbard, 1987; Van Der Stap et al., 2016) and offshore wind turbines (Janßen et al., 2015; Krone et al., 2013). Therefore, it is expected that the expansion of offshore wind in the North Sea would increase the abundance of *M. edulis* (Krone et al., 2013). As such, installation of multiple turbines could increase organic nutrient transfer from the water column in to the sediment layers and, subsequently, enhance inorganic nutrient efflux, influencing primary productivity. Yet these effects may differ between scales, from local scale (close to the turbine), across the OWF, through to the regional scale. This is particularly relevant as OWFs in the southern North Sea, both constructed and in pre-construction phases, are not evenly distributed.

Biological trait analysis (BTA) has emerged as an approach for evaluating ecological functioning expressed over whole assemblages (Bolam and Eggleton, 2014; Bremner, 2008; Bremner et al., 2006b, 2006a, 2003). It is based on the concept that traits associated with life history characteristics, morphology and behaviour influence ecological processes (Bremner et al., 2006a, 2003). BTA quantifies the functional contribution of individual taxa within a community based on trait expression, thereby reducing taxonomic diversity to functional diversity. Application of BTA in marine systems is trailing that in terrestrial and freshwater systems (Bremner, 2008). Nevertheless, progress has been made in applying BTA to describe patterns in ecosystem functioning in marine benthos (Bolam and Eggleton, 2014; Bremner et al., 2003; Paganelli et al., 2012; Shojaei et al., 2015).Here, BTA was applied to community data from soft sediments, rock reefs and offshore platforms in the southern North Sea, which has seen major development from the offshore wind industry.

The analysis in this study was a two-stage process. In the first stage, building on the ground work of chapter 2, a conceptual framework was developed to illustrate the links between biological traits and ecosystem functions and processes. The second stage was the BTA.

4.2 Method

Data used in this study were a subset of datasets analysed in chapter 3. These include the unmanned research platform Fino 1 (P1), the energy platforms K9-A (P2), L10-A (P3), L10-G (P4) and L15-A (P5), natural reefs at Borkum reef ground (R1) and Steingrund near

Helgoland (R2) and soft sediments from development sites for Greater Gabbard OWF (S1), Gallop Extension OWF (S2) and Thanet OWF (S3) (table 2). A detailed account of the sites and the survey methodology is presented in chapter 3 (section 3.2).

4.2.1 Data handling

Eleven biological traits were selected relating to behaviour, morphology and life history characteristics (table 8). These traits can be linked with multiple ecosystem functions that could influence the delivery of ecosystem services (see discussion in section 4.3.1.1). The selected biological traits were divided in to categories. These were used to produce a traits table in which taxa were scored against their affinity for each category. Information regarding taxa expression of traits was taken from published literature, species identification guides (Hayward and Ryland, 2017; Young et al., 2002), online databases (Marine life information network ltd, 2018; Worms Editorial Board, 2018), and personal correspondence with experts. To accommodate taxa with an affinity for multiple categories, fuzzy coding was used to score individual taxa on the extent of their affinity for each category, with scores on the scale of 0- 3 (0 = no affinity, and 3 = total affinity). For example, polychaetes of the genus *Galothowenia* have a strong affinity for sandy seabed, however they are also commonly found in muddy seabed. As such, for preferred substrate, a score of 3 was applied to sand, whilst a score of 2 was applied to mud. A score of 0 was applied to all other substrate. For certain taxa, some attributes could not be accurately scored due to a lack of available information in the literature. As such, these attributes were given a score of 0.

Table 8 Biological traits for epibenthic taxa included for analysis.

Trait	Category	Descriptors
Maximum adult size (length or height)	s10	<10 mm
	s11to100	11-100 mm
	s101to200	101-200 mm
	s200	>200 mm
Larval development	ldD	Direct
	ldLc	Lecithotrophic
	ldPk	Planktotrophic
Larval duration	lduNone	None
	ldu1	<1 day
	ldu2to15	2-15 days
	ldu16to30	16-30 days
	ldu31to60	31-60 days
	ldu60	>60 days
Fecundity	fc10	<10 eggs per brood
	fc10to1000	10 - 1000 eggs per brood
	fc1001to1M	1001 - 1M eggs per brood
	fc1M	>1M eggs per brood
Preferred substrate	subMud	Mud and muddy sand
	subSand	Clean, well sorted sand
	subGrav	Coarse sand and gravel
	subHard	Pebbles and hard substrate
	subBio	Biological (other fauna and flora)
Body shape	mSoft	Soft
	mExosk	Exoskeleton
	mCrust	Crustose
	mCush	Cushion/tunic
	mStal	Stalked
Longevity	l1	<1 year
	l1to2	1-2 years
	l3to10	3-10 years
	l10	>10 years
Strategies for displacement	mobLow	Attached or low mobility
	mobMed	Crawler and burrower
	mobHigh	Swimmer and free
Feeding mode	fS	Suspension (filter)
	fsDF	Selective deposit
	fnsDF	Non-selective deposit
	fScav	Scavenger/Opportunist
	fPred	Predator
	fGraz	Grazer
Bioturbation	bEpi	Epifauna
	bSurf	Surface deposition
	bUp	Upward conveyor
	bDown	Downward conveyor
	bDiff	Diffuse mixing
	bReg	Regulator
Habitat engineering	haReef	Reef builder
	haStab	Sediment stabiliser
	haDest	Sediment destabiliser
	haNone	None

The data for the biological trait analysis consisted of two tables, one containing biological trait scores for taxa and the other containing abundance for taxa at each site. As biological trait analysis uses abundance or biomass data, a subset of the full dataset (presented in chapter 3) for which taxa abundance was available was used. This reduced dataset contained 369 taxa.

Due to large differences in abundance, dominant taxa obscured patterns in co-variation in less-common taxa. For instance, *Jassa* spp. and *Diplosoma* spp. were recorded in samples in the thousands, whereas for *Abietinaria* spp. and *Harmothoe* spp. <10 individuals were recorded per sample. Although it is widely considered that ecosystem functioning is maintained by relatively few, common taxa there is evidence that less common taxa can make significant contributions to ecosystem functioning (Lyons et al., 2005). For this reason, retaining less-common taxa in the analysis was considered desirable. To clearly display patterns in co-variation the mean abundance for taxa at each site was calculated, but there remained substantial divergence in mean abundance between certain taxa. The mean abundance was log+1 transformed to lessen this effect prior to analysis. However, even after transformation, patterns in co-variation in less-common taxa were obscured by those in dominant taxa. Thus, simultaneous analysis of the complete dataset would not yield clearly interpretable results. For this reason the data were further divided into subgroups, shown in table 9, based on the log+1 transformed mean abundance across sites. The biological trait scores for taxa are presented in appendix C.

Table 9 Subgroups of taxa based on sum of log+1 transformed average abundance across all sites.

Group	Mean abundance (log+1 transformed)	No. of taxa
A	>100	14
B	<100 but >10	17
C	<10 but >1	64
D	<1	274

4.2.2 Cluster analysis

Hierarchical clustering is a useful method for exploratory statistics; it produces simple dendrograms from complex multivariate datasets that can be quickly and intuitively interpreted. Hierarchal clustering was performed to view the overall relationship between sites based on the expression of traits within the community. As with some methods of ordination, such as non-metric multidimensional scaling (NMS), hierarchical clustering is based on a dissimilarity matrix (Gardener, 2014). Sites that are similar in their trait expression form clusters and are plotted closer together.

In order to build the dissimilarity matrix, the abundance and trait datasets were amalgamated into a single dataset, in which taxa abundance was weighted by corresponding fuzzy coding for trait expression. Hierarchical clustering was performed in R with the vegan package loaded. A Bray-Curtis method of dissimilarity was used, which is good at detecting underlying ecological gradients (Gardener, 2014). The R code for the cluster analysis is presented in appendix D.1.

4.2.3 Biological traits analysis

Co-inertia analysis (CIA) was considered an appropriate method to analyse correlations between the sample sites and biological trait expression. It is a multivariate method of analysis that enables identification of co-relationships between multiple datasets. Co-inertia axes explain the maximum variance in both datasets simultaneously and describes the closest possible common structure (Marchini et al., 2008). Co-inertia analysis is flexible, allowing axes to be derived by various ordination methods (Dray et al., 2003; Shankar and Paliy, 2016; Thioulouse, 2018; Thioulouse et al., 2015) and can be used for the co-analysis of quantitative and fuzzy variables (Dray et al., 2003). In addition, CIA does not require the datasets to contain the same number of variables (Culhane et al., 2003).

The initial stage was to analyse the traits table using a fuzzy principal component analysis (FPCA) and the sites table using a principal component analysis (PCA) which was mean centred. Co-inertia analysis was then performed to couple the results of the PCA and

FPCA to analyse patterns in their correlation. To aid interpretation, each of the traits were analysed separately. However, when interpreting results, it should be remembered that some traits are inherently interdependent. For example, bioturbation activity is frequently linked to feeding mode and strategies for displacement.

The results of the CIA are interpreted graphically and include a scatter plot of the correlation between sites and traits, a plot of the Y axes weighted by site co-inertia scores and a plot of the X axes weighted by trait co-inertia scores (see figures in section 4.3.2.2. and appendix E). It is important that these plots are interpreted together. The arrows on the scatter plot represent individual taxa. The tips of the arrows show the taxon locations from the PCA and the points (at the base of the arrow) indicate taxon locations from the FPCA. The arrow lengths represent the divergence between the datasets. In other words, the longer the arrow the weaker the site-trait correlation.

The relationship between site and biological traits was measured as the correlation coefficient (RV), which varies between 0 (no correlation) and 1 (perfect agreement) (Thioulouse, 2018; Thioulouse et al., 2015). The significance of the RV, at the 95% confidence level, was then estimated using a Monte-Carlo test, a non-parametric hypothesis test that performs random permutation of the rows of both tables and produces a simulated *p*-value (Thioulouse, 2018; Thioulouse et al., 2015). All analyses and graphics were performed in the R language and statistical environment version 3.3.1 and R studio version 1.1.453, with the ade4 package for multivariate analysis loaded. Graphics were also produced in R and R studio. The R code for the biological trait analysis is presented in appendix D.2.

4.2.4 Conceptual schematic

Based on the conceptual schematic by Causon and Gill (2018) linkages were made between biological traits and ecosystem processes and functions (figure 25). Blue (solid) lines indicate physical habitat changes, and the red (dashed) lines show biodiversity mediated changes. Processes and functions are represented by the dashed boxes and biological traits are shown in the bubbles along the red (dashed) lines.

4.3 Results

4.3.1 Results and discussion of framework

4.3.1.1 Linking biological traits with ecosystem functions and processes

Multiple, interdependent traits influence functions and processes at various levels in marine ecosystems. As illustrated in the conceptual schematic (figure 25), species may cause physical state changes to biotic and abiotic materials through ecosystem engineering activities, modulating the availability of resources to other species (Jones et al., 1994). For example, bioturbation (b), the mixing of sediments by benthic fauna, affects biogeochemical reactions, nutrient cycling, sediment composition and enrichment, and primary productivity (Bertics et al., 2010; Laverock et al., 2011; Stahl et al., 2006; Volkenborn et al., 2010; Welsh, 2010; Zhu et al., 2006). Infaunal invertebrates inhabiting soft-sediments bioturbate during foraging, feeding and burrow maintenance (Dauwe et al., 1998; Meysman et al., 2006; Volkenborn et al., 2010; Welsh, 2010). Through their bioturbation and ventilation activities, infauna suspension and deposit feeders may influence rates of organic matter mineralisation and fluxes of dissolved materials between the sediment and water column (Aller, 1994; Sandnes et al., 2000; Yingst and Rhoads, 1980). For shallow coastal systems inorganic nitrogen regeneration from the sediment may account for 20 to 100% of the annual nitrogen requirements for phytoplankton production (Jørgensen, 1996; Riisgård et al., 1996). Tube ventilation by the polychaete *Lanice conchilega* introduces oxygen-rich water deep in to the sediment (Forster and Graf, 1995) having marked effects on benthic respiration, nutrient release and denitrification (Braeckman et al., 2010).

Habitat engineers (ha) can also generate biologically mediated habitat (figure 25). Tube structures built by polychaetes *L. conchilega* and *Sabellaria spinulosa* can aggregate sediments and form biogenic reefs (Braeckman et al., 2014; Callaway et al., 2010; De Smet et al., 2015; Flavia et al., 2018; Hendrick and Foster-Smith, 2006; Maddock, 2008; Rabaut et al., 2009; Van Hoey et al., 2008). In doing so, *L. conchilega and S. spinulosa* provide shelter, feeding grounds and opportunities for settlement for a wide variety of species (De Smet et al., 2013; Maddock, 2008; Petersen and Exo, 1999; Rabaut et al., 2013). *L. conchilega* has been shown to increase biodiversity in soft sediment ecosystems (Rabaut et al., 2009; Van Hoey et al., 2008).

Hard structures produced by marine molluscs and polychaetes that provide habitat can also influence fluid flow and sediment transport (Gutiérrez et al., 2003). Flow perturbation has been positively correlated with the height and diameter of the protruding structure (Eckman and Nowell, 1984; Grant et al., 1992). Densely packed mussel and oyster beds have been shown to perturb fluid flow and sediment transport close to the sea bed (Gutiérrez et al., 2003).

As perturbation of fluid flow has been positively correlated with structural dimensions, it could be surmised that size would also affect fluid flow and sediment transport. It has been noted that size is of particular importance where ecosystem functions relate to biogenic habitat or biological mediation of energy fluxes (Norkko et al., 2013). Maximum adult size (s) was also linked with energy and nutrient cycling, primary production and nitrogen fixation (Figure 25). It has been shown that body mass affects metabolic rate, energy demand and uptake rate (Peters, 1983; Reiss et al., 2009; Woodward et al., 2010). Thus, it is likely maximum adult size of species within a community would influence the delivery of ecosystem services.

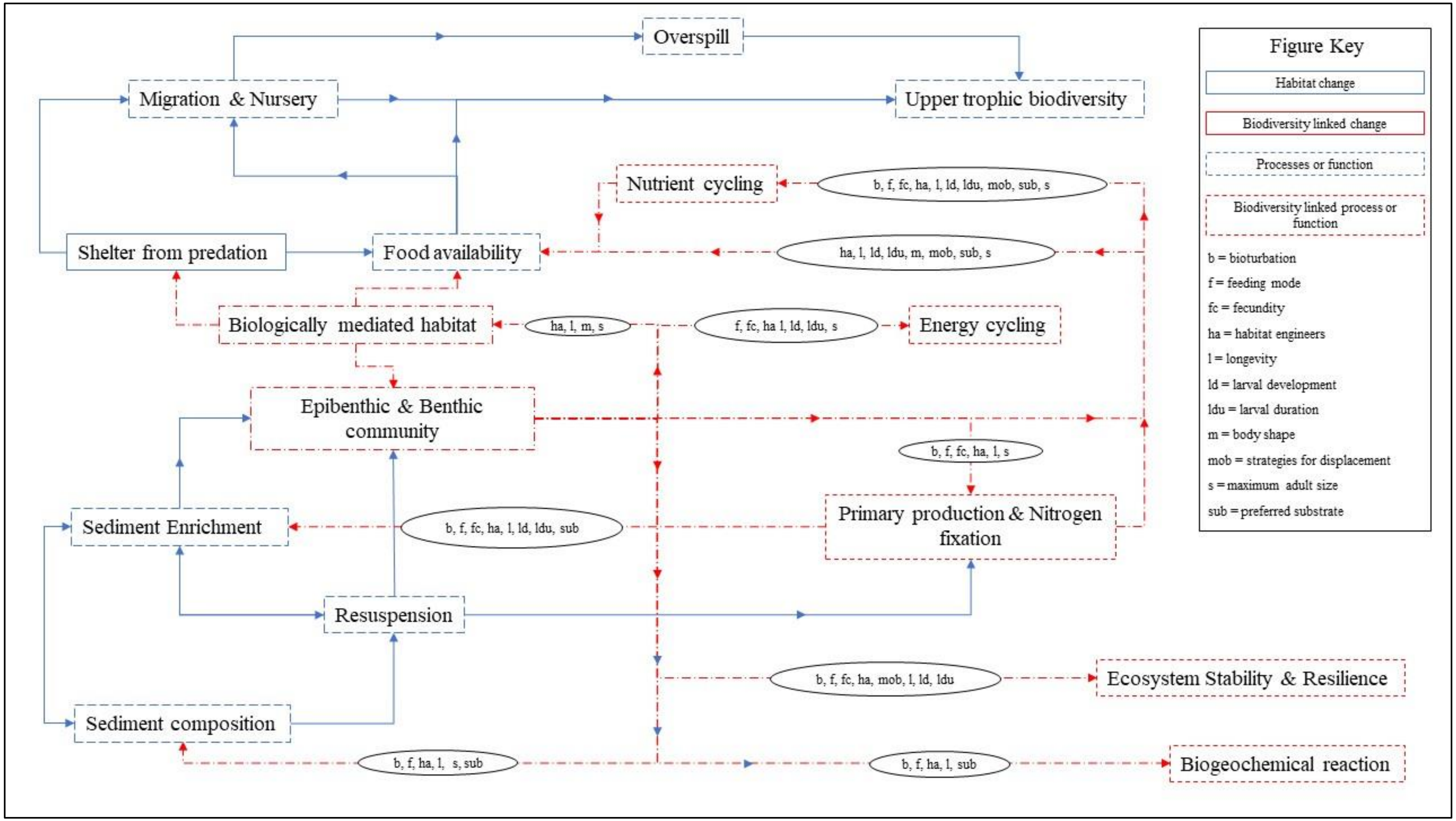

Figure 25 Conceptual schematic demonstrating links between ecosystem functions and processes, and biological traits (modified from Causon and Gill, 2018).

4.3.2 Results of the biological traits analysis

4.3.2.1 Cluster analysis

In general, two main clusters were identified for each trait, with platforms P1-5 and the rock reef R1 comprising the first cluster, and the soft sediments S1-3 and rock reef R2 in the second cluster (figure 26a-c). The results therefore indicate that trait expression was similar between the platforms and the rock reef site, R1 and between the soft sediment sites and the rock reef site R2. However, clusters differed for longevity (figure 26b). Thus, for longevity P1 and P2 appeared to be more similar to the soft sediment sites and R2 than to P3-5 and R1.

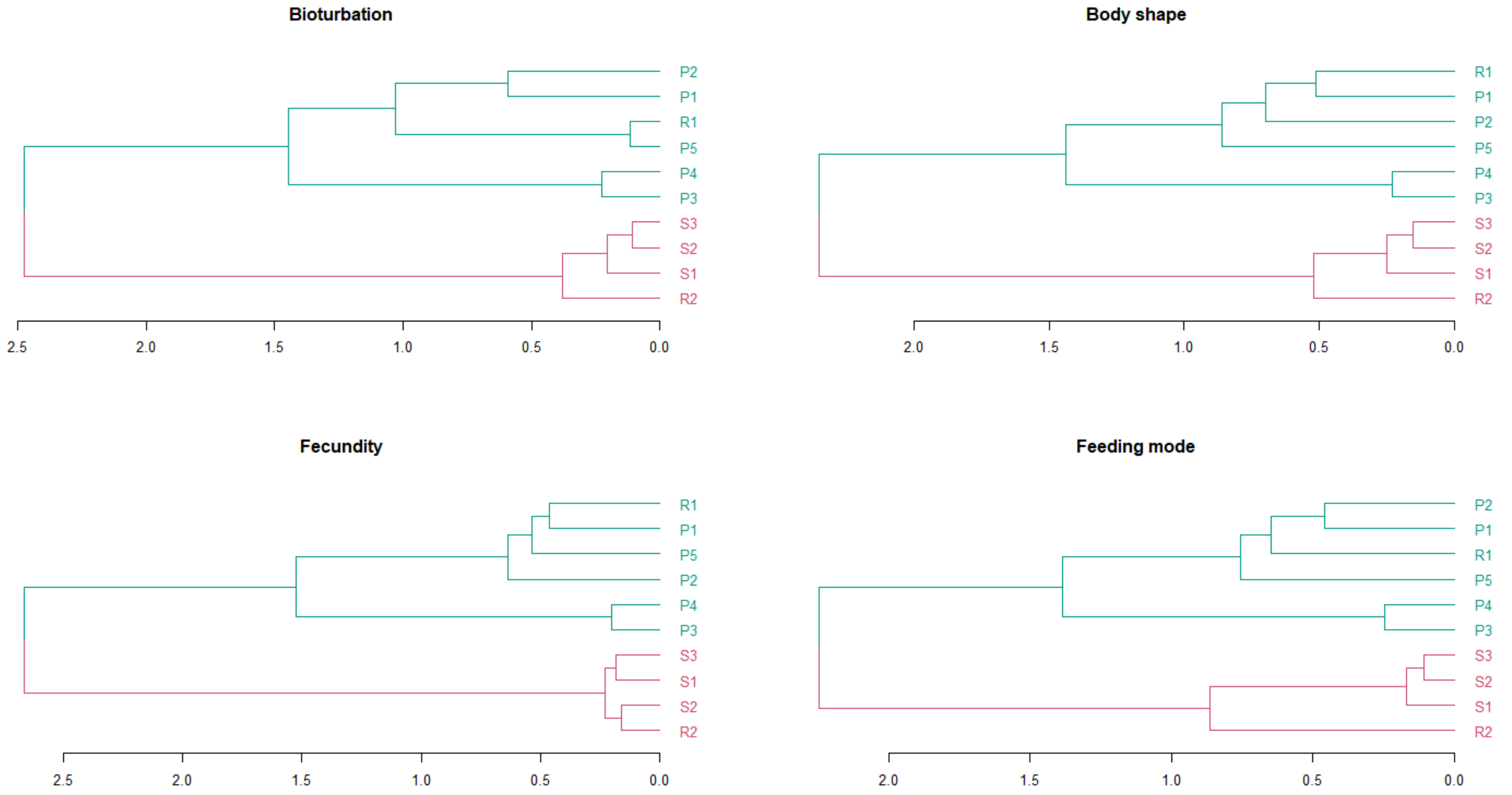

Figure 26a Cluster analysis illustrating the level of similarity in trait expression between sites, based on biological trait scores weighted by taxa abundance. Two clusters were identified for each trait. Clusters were coloured red and green to aid interpretation.

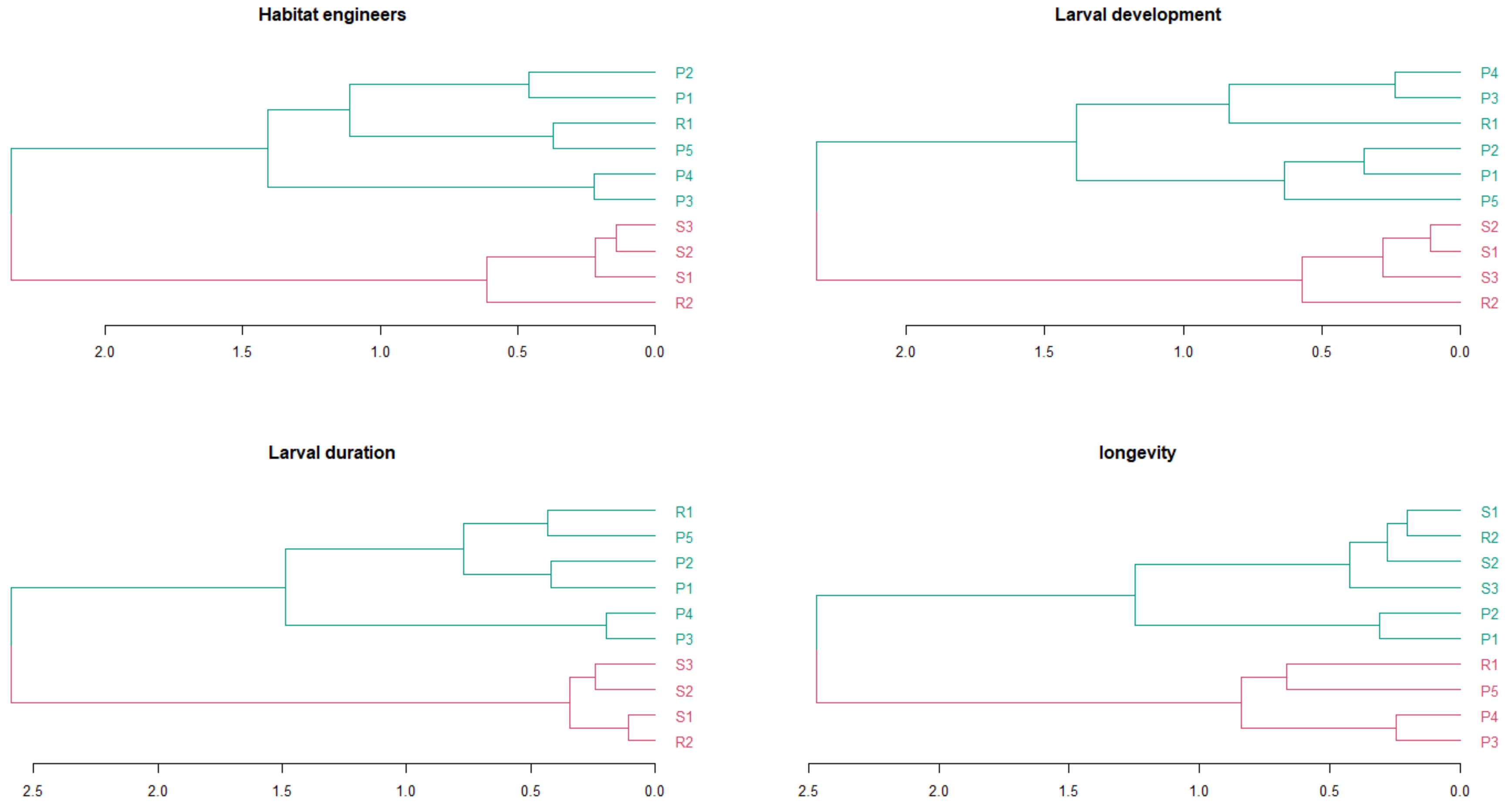

Figure 26b Cluster analysis illustrating the level of similarity in trait expression between sites, based on biological trait scores weighted by taxa abundance. Two clusters were identified for each trait. Clusters were coloured red and green to aid interpretation.

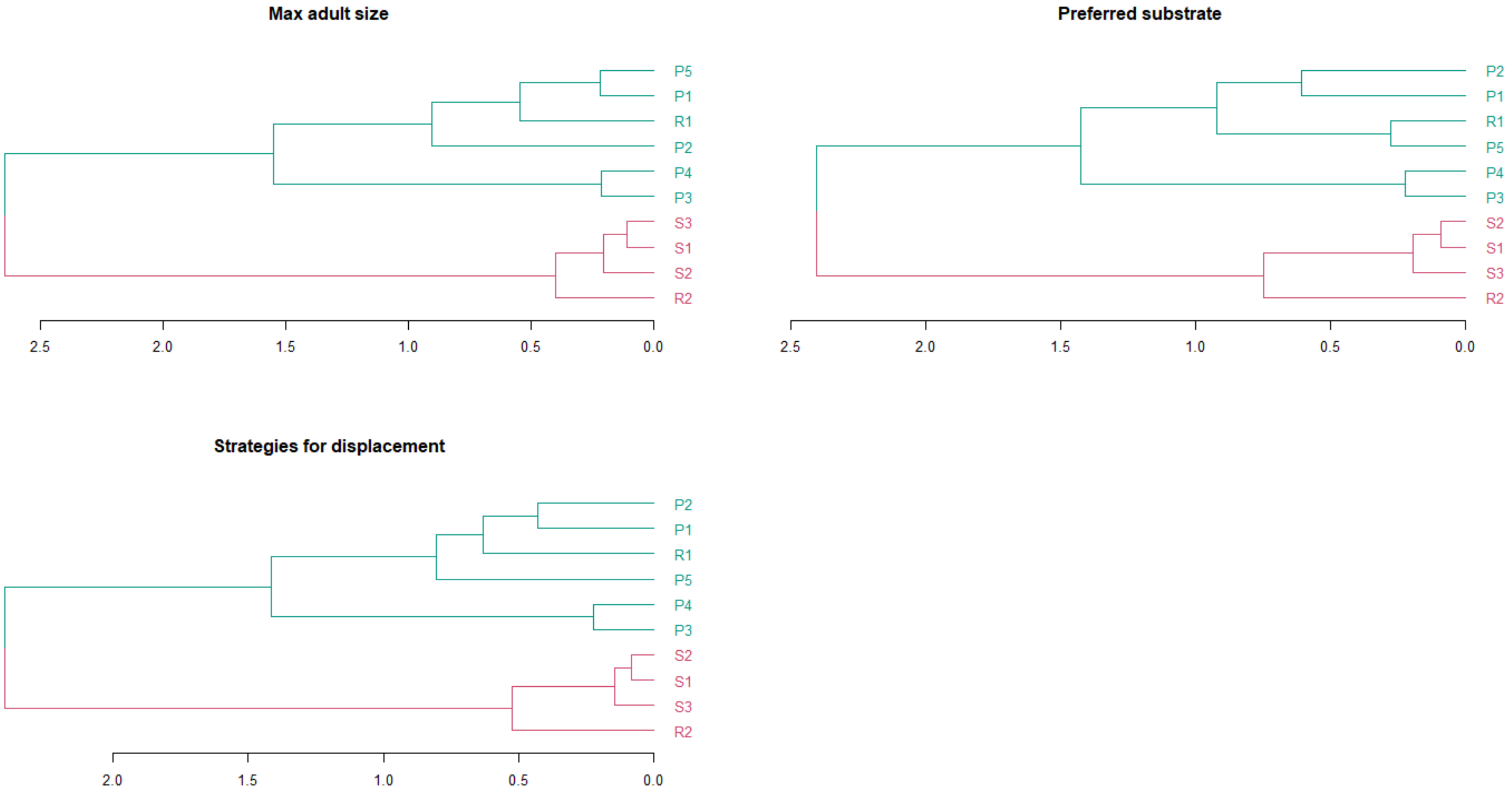

Figure 26c Cluster analysis illustrating the level of similarity in trait expression between sites, based on biological trait scores weighted by taxa abundance. Two clusters were identified for each trait. Clusters were coloured red and green to aid interpretation.

4.3.2.2 Co-inertia analysis

Due to the number of plots produced through the CIAs only those for which correlation coefficients were found to be significant at the 95% confidence interval (*P* <0.05) are presented here. The remaining graphics from the CIAs are presented in appendix E.

For group A, platforms P1-5 showed similar expression of traits (appendix E, figure E-1 – E-11). Although, trait expression was also similar between P5 and R1-2. The soft sediment sites S1 and S3 were more similar to each other than they were to S2. For example, bioturbation, the mixing of sediments by marine organisms, was characterised by epifauna and surface deposition for group A at platforms P1-3, and by epifaunal dwelling only for P5, R-2. Whereas surface deposition characterised S1 and S3. For fecundity communities from the platforms were dominated by taxa with affinities for larval counts 0 to $\leq$1000. Soft sediment sites, particularly S1 and S3, were dominated by fecundities of 10 to 1 million. In rock reef communities, amongst the most abundant taxa no level of fecundity characterised the sites. Yet, for group A the Monte-Carlo test showed no significant site-trait correlations amongst group A taxa (appendix F, table F-1).

Amongst group B taxa the expression of traits in platform communities were generally comparable (appendix E, figure E-12 – E-21). As was trait expression by group B taxa in rock reef and soft sediment communities. Yet, there were no clear trends in trait expression between habitat types. For instance, in the bioturbation category there was a strong affinity for epifauna and surface deposition across all habitat types, although diffuse mixing also characterised platforms. Moreover, taxa with an affinity for hard substrata were relatively abundant at soft sediment sites as well as platforms and rock reefs. Taxa with an affinity for mud and sand were relatively abundant at platforms and the rock reef R1. However, the Monte-Carlo test indicated significant site-trait correlations within feeding modes (appendix F, table F-2). All other site-trait correlations for group B taxa were not found to be significant.

Figure 27a-d illustrate results of the feeding mode CIA for group B. Figure 27a-c are separated in to 4 quadrants. The position of taxa in figure 27a corresponds to the position of sites in figure 27b and traits in figure 27c. Based on the CIA output, the expression of feeding modes amongst group B taxa was similar between platforms P1, P2, P5 and soft sediment sites S1 and S3. Trait expression was also similar between P3 and R1. Thus, although there were significant site-trait correlations, these correlations did not appear to associate with habitat type.

The graphs illustrate that taxa with a strong affinity for scavenging, such as *Pinnotheres spp* (Pinn), and deposit feeding (selective and non-selective), such as *Lagotia viridis* (Lago), were relatively abundant at platform sites (P1, P2, P4 and P5) and soft sediment sites (S1 and S3) (bottom right quadrant figure 27b and c). The short arrows in the bottom right quadrant of figure 27a suggest strong site-trait correlations for these taxa.

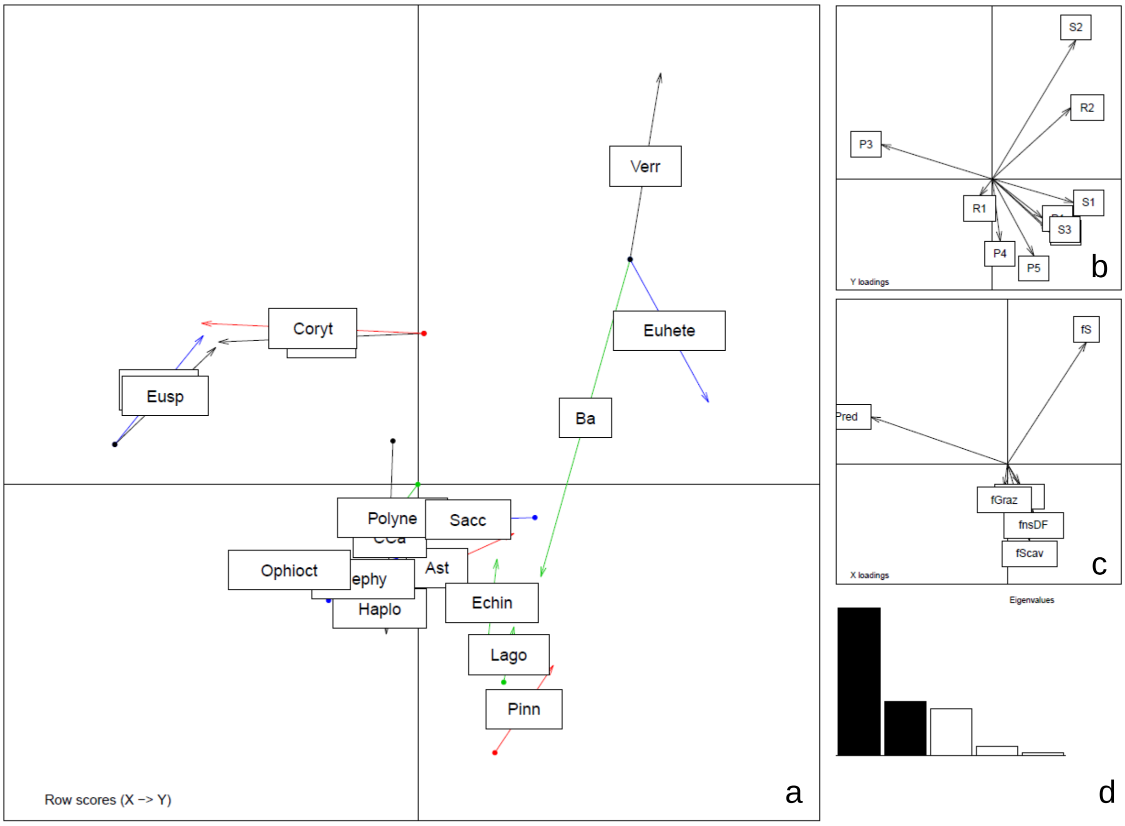

Figure 27 Group B co-inertia analysis for feeding mode. Plot (a) shows the correlation between sites and traits, (b) shows the coefficients of sites and (c) shows the coefficients of biological traits. These plots are separated in to 4 quadrants. The position of arrow heads in (a) corresponds to the position of sites in (b) and the position of dots in (a) corresponds to the position of biological traits in (c). Short arrows in (a) indicate a strong correlation between sites and biological traits, whereas long arrows indicate a weak correlation. Colours in (a) were added to aid differentiation between arrows. The screeplot (d) shows the eigenvalues for the co-inertia analysis. As axes 1 and 2 accounted for most of the variance in feeding mode composition (77% in total, with 56% of inertia projected on to axis 1 and 21% on to axis 2) only axes 1 and 2 were retained in the analysis. Taxon names associated with codes are provided in appendix C (table C-1).

As shown in figure 27a-c, taxa with a strong affinity for predation, such as *Corynactis spp* (Coryt) and *Euspira spp* (Eusp), dominated P3 (top left quadrants). Whereas taxa with a strong affinity for suspension feeding, such as *Verruca spp.* (Verr) and *Euheterodonta* (Euhete), dominated S2 and R2 (top right quadrants). However, the site-trait correlations were weaker.

For group C (appendix E, figure E-22 – E-31) S1-3 were generally similar in trait expression. Further, feeding mode, and larval development and duration were equal between P5 and R1, as was bioturbation, body shape and strategies for displacement between R1 and R2. The Monte-Carlo test indicated significant site-trait correlations within longevity for group C (appendix F, table F-3). All other site-trait correlations for group C taxa were not found to be significant.

Figure 28 illustrates the results of the longevity CIA for group C. The output shows that taxa with an affinity for 1-2 years life-spans dominated sites S1, S3 and P2-P4. Sites P1 and R1 were characterised by taxa with an affinity for >10-year lifespans, and P5 by taxa with an affinity for <1-year life spans. However, for some of these taxa, such as *Copepoda* (Cop) and *Mytilidae* (Myti), the arrows appeared relatively long (figure 28a), indicating weak site-trait correlations.

Site R2 was dominated by taxa with an affinity for lifespans of 3-10 and >10-years, such as *Polycarpa spp* (Polyca), for which site-trait correlations were relatively strong (figure 28a). S2 was dominated by taxa with an affinity for 1-2 year and 3-10 year lifespans, such as *Ophiuroidea* (Ophi) for which site-trait correlations were strong, and *Sabellaria spp* (Saber), for which site-trait correlations were weak.

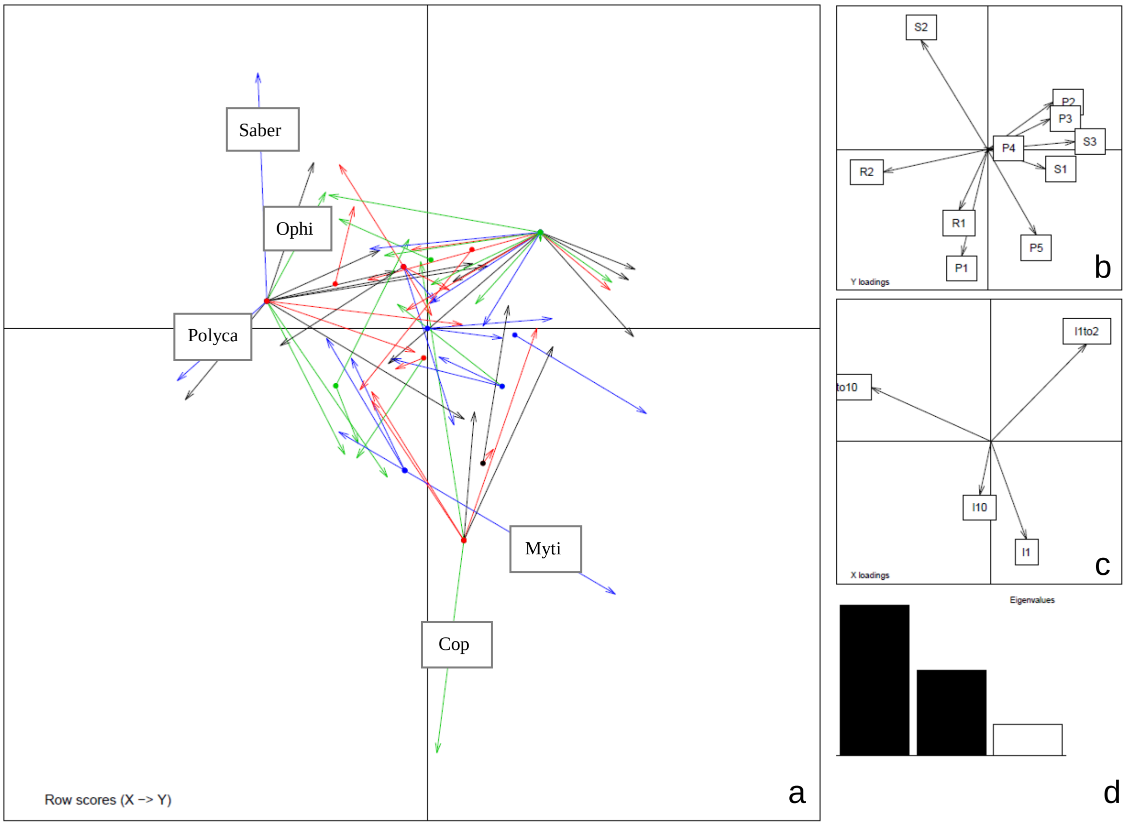

Figure 28 Group C co-inertia analysis for Longevity. Plot (a) shows the correlation between sites and traits, (b) shows the coefficients of sites and (c) shows the coefficients of biological traits. These plots are separated in to 4 quadrants. The position of arrow heads in (a) corresponds to the position of sites in (b) and the position of dots in (a) corresponds to the position of biological traits in (c). Short arrows in (a) indicate a strong correlation between sites and biological traits, whereas long arrows indicate a weak correlation. Colours in (a) were added to aid differentiation between arrows. The screeplot (d) shows the eigenvalues for the co-inertia analysis. As axes 1 and 2 accounted for most of the variance in feeding mode composition (88% in total, with 56% of inertia projected on to axis 1 and 32% on to axis 2) only axes 1 and 2 were retained in the analysis.

As with group C, trends in trait expression for group D (the least abundant taxa) were not clear (appendix E, figure E-32 – E-41). Although, trait expression was similar between P5 and R1 for bioturbation, fecundity, longevity and strategies for displacement. The Monte-Carlo test (appendix F, table F-4) indicated that the correlation coefficients group D larval duration were statistically significant. All other site-trait correlations for group D taxa were not found to be significant.

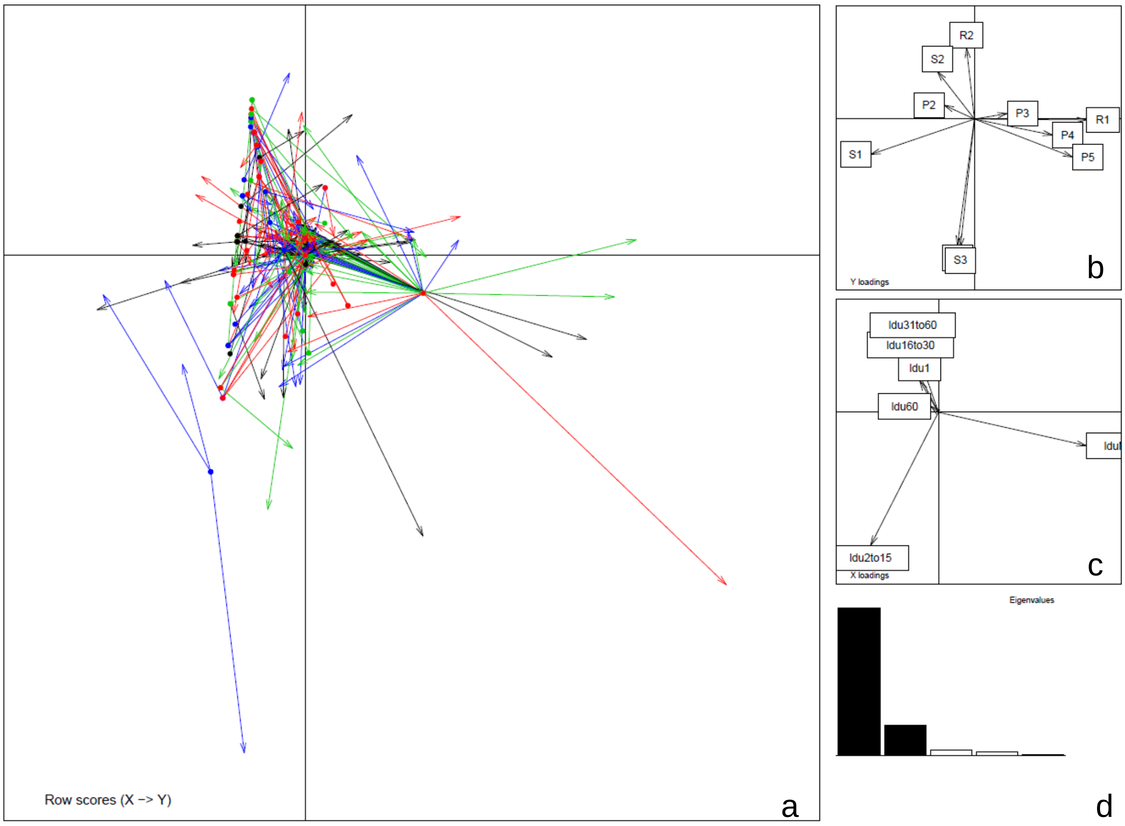

Figure 29 Group D co-inertia analysis for Larval duration. Plot (a) shows the correlation between sites and traits, (b) shows the coefficients of sites and (c) shows the coefficients of biological traits. These plots are separated in to 4 quadrants. The position of arrow heads in (a) corresponds to the position of sites in (b) and the position of dots in (a) corresponds to the position of biological traits in (c). Short arrows in (a) indicate a strong correlation between sites and biological traits, whereas long arrows indicate a weak correlation. Colours in (a) were added to aid differentiation between arrows. The screeplot (d) shows the eigenvalues for the co-inertia analysis. As axes 1 and 2 accounted for most of the variance in feeding mode composition (95% in total, with 78% of inertia projected on to axis 1 and 16% on to axis 2) only axes 1 and 2 were retained in the analysis.

Figure 29a-d illustrates the results for the larval duration CIA for group D. Generally, taxa associated with platforms had relatively short larval durations. P1 and S3 were characterised by a larval duration of 2-15 days. Sites P3-5 and R1 were characterised by a larval duration of 0 days.

P2 differed from other platforms as there were no overriding site-trait correlations. Whereas R2 and S2 were dominated by taxa with affinities for larval durations of 16-30 and 31-60 day. Further, S1 was dominated by taxa with larval durations of 2-15, 16-30 and 31-60 days. Thus S1, S2 and R2 were generally characterised by longer larval durations.

Due to the larger number of taxa in group D, interpretation of figure 29a is challenging. Site-trait correlations for taxa with larval durations of <1, 16-30 and 31-60 days located at sites P2, S2 and R2 were generally stronger than for other taxa, as illustrated by shorter arrows in the top left quadrant.

4.4 Discussion

There is mounting evidence that benthic biodiversity differs between artificial and natural substrate (chapter 3; Connell and Glasby, 1999; Coolen et al., 2018; Petersen and Malm, 2006). But it is not fully understood how changes in biodiversity would influence ecosystem functioning. This study set out to determine whether ecosystem function differs between natural substrates and offshore energy structures, which have been shown to differ in community composition (chapter 3). The results of hierarchal cluster analysis suggested that biodiversity was linked to functional diversity, which was linked to habitat (or structure) type. In chapter 3 it was shown that community composition at P1-5 was more similar to R1 than to R2 and S1-3. Further, communities at R2 were more similar to S1 and S3 than to other sites. Through the hierarchal cluster analysis two major clusters were identified for each trait. Typically the first cluster comprised platform sites and the rock reef site R1.

Previous analyses indicated differences in community composition between P5 and R1 were not significant (chapter 3) and these sites were shown to be linked within the results of the cluster analysis for most traits. These sites shared several key characteristics. Unlike at P1-4, samples from P5 were taken from the scour protection layer only, which consisted of rocks and boulders. Further, R1 and P5 are similar in depth (28 and 22 m respectively) and distance from shore (30 and 41 km respectively). Indeed, depth and distance from shore have been shown to have a significant effect on biodiversity, as has substrate type in combination with depth (chapter 3; Coolen, 2017; Van Der Stap et al., 2016). In addition, sites P3 and P4 were not significantly different, based on β-diversity, and were similar in terms of their substrate type (steel platforms with rock/boulder scour protection) and depth. Although P3 and P4 differed in their distance from shore (41 and 84 km respectively).

The second cluster generally included the soft sediment sites and R2 (figure 26a-c). Typically, trait expression was more similar between S1-3 than they were to R2. Previous studies found no significant difference in community composition between S2 and S3 (chapter 3). The composition of clusters differed for longevity (figure 26b), whereby the P1 and P2 were clustered with the soft sediment sites and R2. Therefore, the hierarchal cluster analysis indicated that trait expression was generally similar between the platforms and R1, and between the soft sediments are R2. This indicates that a change in biodiversity following the installation of an OWF would result in a change in ecosystem functioning. However, for the expression of longevity, site P1 and P2 were more similar to the soft sediments and R2 than to the other platforms and R1.

Co-inertia analysis was performed to further explore differences in functional diversity between habitat types. Prior to analysis data were separated in to sub-sets based on mean abundance which allowed trends amongst rarer taxa to be viewed more clearly through CIA. For the higher abundance groups (A and B) CIA analysis generally agreed with the cluster analysis, showing similar characteristics amongst the platform communities and amongst the soft sediment communities, whilst communities at the two substrate types differed from each other. Rock reefs occupied the margins between platforms and soft sediments. Group A trait expression was similar between rock reefs, but for group B, trait expression at R1 was more similar to P5, and R2 was more similar to the soft sediment sites. For the lower abundance groups, trends were not clearly defined, although generally trait expression was similar amongst soft sediment sites for group C, and between P5 and R1 for both groups C and D.

Despite differences in community structure (chapter 3) the results of the Monte-Carlo tests do not provide compelling evidence ecosystem functioning would change following the installation of an OWF. For most of the biological traits, including all those for the dominant taxa, the correlations between site and traits were not significant ($P > 0.05$). Thus, the results suggest that artificial structures broadly support similar functional diversity to natural habitats. This finding supports that of Bremner et al (2003), who demonstrated that subtidal sites in the southern North Sea and eastern English Channel (ICES divisions IVc and VIId respectively) differed in relative taxon composition but were similar in terms of their biological trait structure. They noted that different taxa were fulfilling the same ecological functions at each site. However, CIA correlation coefficients were significant ($P < 0.05$) for feeding mode in group B, longevity in group C and larval duration in group D.

It can be tempting, from this method of analysis, to view biological traits as separate entities that contribute to functions. However, it is important to keep the underpinning biology of organisms in mind when interpreting the results. As previously discussed, biological traits are closely linked characteristics and often are interdependent. Feeding modes have been shown to be influential in structuring communities (Bremner et al., 2003; Pearson and Rosenberg, 1987). Further, along with sediment composition and enrichment, feeding mode can be linked with nutrient and energy cycling, biogeochemical reactions and ecosystem stability and maintenance (figure 25). As such, feeding modes influence the flow of ecosystem services including food provision and waste treatment.

Figure 27a shows that platforms (P1-2, P4-5), soft sediment sites (S1 and S3) and the rock reef R1 are characterised by scavengers and deposit feeders (selective and non-selective). For example, Echinoidea and *Lagotia* spp., which have an affinity for deposit feeding were recorded in relatively high abundance at P5. Echinoidea were also recorded in relatively high abundance at S1, whist *Lagotia* spp. was recorded in relatively high abundance at S3.

Sites S2 and R2 on the other hand were characterised by suspension feeders, which bring energy into reef systems from the water column as they feed on phytoplankton and suspended particulate matter (Dame and Patten, 1981). Organic matter deposited by suspension feeders makes energy available for other organisms, such as deposit feeders (Dame and Patten, 1981). As previously discussed, through their feeding activities deposit feeders have a role in transporting organic matter in to sediments (Aller, 1994; Sandnes et al., 2000; Yingst and Rhoads, 1980) and regenerating inorganic nitrogen from the sediments (Jørgensen, 1996; Riisgård et al., 1996). Thus, deposit feeders also influence primary productivity, which can be linked with climate regulation as increased productivity can support greater biomass and increase carbon storage.

The lifespan of taxa was linked with all functions and processes (figure 25) as it is also a measure of the duration of trait expression, although there will undoubtedly be variation in trait expression over an individual's life span. Typically, platforms and in soft sediments (particularly P2-P5, S1 and S3) were characterised by taxa with short (<1-2 years) life spans. Taxa with longer lifespans (3-10+ years) characterised the rock reefs. Although for some taxa, such as *Copepoda*, these correlations were relatively weak.

Larval duration was conceptually linked with ecosystem stability and resilience, as well as secondary habitat (figure 25). It was once assumed that populations were open and larval transport typically occurred over hundreds to thousands of kilometres (Caley et al., 1996; Cowen and Sponaugle, 2009; Stobutzki, 2001). However, it has been demonstrated that larval retention occurs frequently in the natural habitat (Almany et al., 2007; Hellberg et al., 2002; Levin, 2006). For example, for a variety of coastal and intertidal invertebrates, including intertidal barnacles, larvae remained within 5 km of the shore (Shanks et al., 2002; Shanks and Brink, 2005; Shanks and Shearman, 2009). Yet, the common occurrence of coastal and intertidal invertebrates on offshore structures indicates that offshore transport does occur, either through natural processes (tides, currents and spawning in colonising communities) or shipping (vessel hulls or ballast water). Long larval durations increase the possibility that adverse hydrodynamic events, such as storms, would displace larvae from the adult environment (Shanks, 2009), reducing the chance they would settle and survive to the adult life stage. This notwithstanding, as natural hard substrate is uncommon in the offshore environment, for larvae transported away from the coast a long larval duration may increase the likelihood of encountering suitable substrate.

Platforms (P1, P3-5), R1 and S3 were characterised by larval durations of ≤15 days. Whereas R2, S1 and S2 were characterised by larval durations of 2-60 days. Trait correlations for taxa located at sites S2 and R2 were generally stronger than for other taxa (figure 29a). Nonetheless, these results should be interpreted with caution. There was considerable variation in the availability of data on biological traits (appendix C). For example, it was found that extensive records existed for strategies for displacement, maximum adult size and feeding modes for benthic invertebrates, with few taxa for which this information was unavailable (approximately 2%, 3% and 5% respectively). Whereas, knowledge gaps were much greater for fecundity and larval duration. Information on these traits were unavailable for approximately 25% of the taxa included in this study but would likely strengthen trends were it available and could further elucidate the functions of these taxa within the system.

It would be unreasonable to assume that the results presented here could be applied to all turbines within a wind farm, and to all OWFs equally. The offshore energy platforms included in this study stand in isolation. From an ecological perspective an OWF can be viewed as a network of artificial reefs (Causon and Gill, 2018). Typical separation between turbines is 500-1000 m, which is within the migratory range of many mobile hard bottom species (Krone et al., 2013a; Snyder and Kaiser, 2009) and the dispersal range of many larvae (Kinlan and Gaines, 2003). As such, colonising communities are not independent; they would be influenced by communities on other turbines within the OWF. It is also likely that the turbine substructures would themselves influence the environmental conditions within the OWF. For instance, turbine foundations effect the hydrodynamic flow, generating turbulent wakes downstream of the turbines that may be 30-150 m wide and several km long (Li et al., 2014; Miles et al., 2017; Rogan et al., 2016; Vanhellemont and Ruddick, 2014). Satellite imagery (Vanhellemont and Ruddick, 2014) and aerial photographs (Baeye and Fettweis, 2015) suggest that suspended particulate matter collected in wakes could impact water quality kilometres downstream. At Thanet, wind farm plumes that appear to be >10 km in length have been recorded (Vanhellemont and Ruddick, 2014).

4.5 Conclusions

With continued large-scale development in offshore renewable energy, understanding how changes in the composition of benthic communities' influence functioning in marine communities is vital if ecosystem services are to be sustained.

To better understand how changes in biodiversity influence ecosystem functioning we need to understand how individual taxa contribute to natural processes. Biological traits analysis is an approach that has been used to quantify ecosystem functioning. Taxonomic diversity is reduced to functional diversity based on a species expression of traits, such as feeding mechanisms, body shape and size, or reproductive strategy. Biological traits can be linked to natural processes that support functions. Thus, BTA can be applied to demonstrate functional change following the installation of an OWF. Through monitoring functional diversity rather than species richness we can provide a measure of change that is meaningful to the provision of ecosystem services.

The results of this study indicated that differences in the expression of some traits between the soft sediments, natural rock reefs, and artificial platforms were significant whilst the majority were not significant. Differences were significant for feeding in common taxa (group B), and longevity and larval duration for less-common taxa (groups C and D). Yet differences were not significant for dominant taxa (group A). As such, any subsequent differences in functioning may well be muted. Thus, the results of this study imply that, at the local scale at least, ecosystem functioning between an offshore wind turbine and the natural substrate would be similar overall, despite differences in biodiversity. Therefore, we could expect the flow of ecosystem services within OWFs to be similar to natural benthic habitats. However, it should be noted that, as the CIA necessitated abundance or biomass data, some taxa were not included in the analysis. In particular, colonial taxon, such as those in the phyla Bryzoa and Entoprocta and the class Hydrozoa, were recorded simply as present/absent. As such, their contribution to ecosystem functioning was not quantified in this analysis.

Moreover, as well as differences in habitat types, there was a difference in the geographic distribution of the sample sites. As sites differ in other characteristics (depth, salinity, current regime etc) it is likely biogeography would contribute to the observed results. Further, the analysis was performed at the level of the structure and it is unclear how the trends observed would scale up across an OWF, or multiple OWFs, as those in the southern North Sea are not evenly distributed. In addition, offshore wind turbines are not geographically isolated and it should not be assumed that ecosystem functioning in colonising communities would be the same on all turbine foundations. Future efforts to quantify the influence of offshore wind turbines on ecosystem functioning should consider the proximity, and biological connectivity, of OWFs. Greater connectivity between turbines and OWFs could increase resilience in ecosystem functioning, ensuring the delivery of ecosystem services in the face of environmental impacts.

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Chapter 5: A Comparative Assessment of Natural Capital and Ecosystem Services Before and After the Construction of an Offshore Wind Farm – the case of Thanet Offshore Wind Farm

5.1 Introduction

The United Nations (UN) adopted sustainable development goals which, although not legally binding, are intended to provide a pathway for nations to eliminate poverty, secure equitable livelihoods and safeguard the environment and natural resources (Sullivan et al., 2018; United Nations, 2015). With an ever growing population (which may reach 10 billion worldwide by 2100) and the threat of climate change (Guerry et al., 2015), meeting energy needs whilst promoting environmental sustainability will be a challenge.

A consensus has emerged that the minimum level for sustainable development is that which prevents natural capital from diminishing (Costanza and Daly, 1992; Markandya and Barbier, 1989; Yang and Hu, 2018). Natural capital relates to stocks of natural assets in ecosystems that generate resources or services (Costanza and Daly, 1992; Hinterberger et al., 1997; Natural Capital Committee, 2014). The UK government has made the commitment that the current generation should leave the natural environment of England in a better state than in which it was found (HM Government, 2011; Natural Capital Committee, 2017a). To achieve this goal the UK government has set out a 25 year plan to improve the environment with the natural capital approach at the core (HM Government, 2018). Additionally, the EU biodiversity strategy 2020 aims to improve policy on nature conservation, biodiversity protection and natural capital assessment (Picone et al., 2017). Careful investment in natural capital is intended to secure those assets so as to provide a sustainable flow of benefits, including ecosystem services (Natural Capital Committee, 2017a).

It is internationally agreed that increasing renewable energy capacity is necessary to balance energy needs with carbon emission targets (Choi, 2018; European Commission, 2018a, 2018b; Masson-Delmotte et al., 2018). However, marine renewable energy structures have the potential to modify ecosystems, biodiversity and ecosystem functions (chapters 3 and 4). Thus, offshore wind farms (OWFs) can effect natural capital (the stocks of resources on which society depends) in marine and coastal ecosystems (Natural Capital Committee, 2017a).

Under current regulations, an Environmental Impact Assessment (EIA) is required for certain developments, including offshore wind energy. An EIA is intended to inform local planning authorities of the likely significant environmental effects of that project (UK Government, 2017). In the case of an OWF this involves conducting baseline surveys of the development area to identify biota and habitats that would be at risk from the construction and operation of the wind turbines. However, there are concerns that the EIA framework does not adequately capture changes in natural capital assets that affect sustainability, particularly for renewable energy developments (Hooper et al., 2017b; Smart et al., 2014; Willsteed et al., 2018). A key criticism is that EIAs emphasise negative impacts and take a siloed approach to issues, thus being less effective at taking an integrated systems based approach and evaluating positive and non-local benefits (Hooper et al., 2017b; Smart et al., 2014).

Natural capital assessment (NCA) offers an additional approach for planning and continued environmental monitoring that incorporates both positive and negative changes across multiple scales. The natural capital committee (NCC) provide guidance on performing an NCA (Natural Capital Committee, 2017a). The steps outlined in the natural capital committee's guidance are summarised in table 10.

The NCC's methodology involves identifying natural assets and services in place, along with their current extent and condition. In addition, an asset risk register is developed to highlight threats to assets and services. Once compiled this evidence is used in developing options to manage natural capital in order to create new value and opportunities (Natural Capital Committee, 2017a). This approach has been applied to localised and terrestrial systems and across regions (Deane and Walker, 2018; Lovett et al., 2018; RSPB, 2017).

Table 10 Natural capital assessment steps.

Step 1	Setting out the vision
Step 2	Understanding where you are starting from
Step 3	Building the evidence base
Step 4	Identifying and weighing up your options
Step 5	Implementation and evaluation

Whilst value is at the heart of the natural capital concept (Natural Capital Committee, 2017b), much of natural capital does not pass through markets and as a result biodiversity often falls victim to competing claims on nature and its use (European Commission, 2011). Therefore, monetary valuation on its own is an unreliable means of assessing natural capital for informing long-term sustainability of ecosystems and provision of goods and services (Monfreda et al., 2004). Further, markets for natural capital and flows of ecosystem services are often missing or incomplete (Fenichel and Abbott, 2014). This is particularly true for marine systems, which have received less focus in the assessment of natural capital and ecosystem services than their terrestrial counterparts. It has been recommended that a marine NCA should be undertaken to increase understanding and evidence of the extent of assets, services and benefits from the sea, coastal waters and estuaries (Natural Capital Committee, 2019).

As further investment in offshore wind energy is expected, which will see the installation of thousands of new structures in coastal and marine regions (chapter 3), understanding the effects of OWFs on natural capital and ecosystem services is evidently necessary. The NCA approach (table 10) has been used to structure the analysis within this chapter.

5.2 **Setting out the vision**

This case study aims to assess how installing an OWF would affect natural capital and the flow of ecosystem services. The methodology will be based on that laid out in the NCC's 'How to do it: a natural capital workbook' (Natural Capital Committee, 2017a). In performing an NCA for an OWF this study attempts to provide a new perspective on the subsequent change in the benthic habitat and biodiversity.

It is recognised that there is paucity of available data for assets in marine systems. Baseline data presented here were collected during pre-installation benthic surveys of biological resources performed as part of an EIA (Marine Ecological Surveys Ltd, 2008). The NCA process is intended to identify stocks and trends in natural capital. Thus, in performing an NCA knowledge gaps that cannot be filled using current data can be ascertained. Therefore, constraints in EIAs in assessing natural capital will be highlighted; the adequacy of current survey activities can be considered and the benefits of additional monitoring may be evaluated.

5.3 **Understanding where you are starting from**

5.3.1 Thanet wind farm development site

Thanet OWF is located in the southern North Sea, within the Outer Thames Estuary (figure 30; Haskoning UK Ltd, 2013). It is owned and operated by Thanet Offshore Windfarm Limited, a subsidiary of Warwick Energy Limited. Thanet OWF received consent in December 2006 (Haskoning UK Ltd, 2013) and was opened in 2010 (4C Offshore, 2018). Thanet consists of 100 vestas V90 3 MW turbines constructed on monopile foundations and covers an area of approximately 35 km^2 (4C Offshore, 2018; Haskoning UK Ltd, 2013; Marine Ecological Surveys Ltd, 2008). Depths within the OWF range from 15-27 m (Pearce et al., 2014). Thanet OWF was selected due to the availability of pre-installation benthic biodiversity data for this site.

This natural capital assessment is particularly relevant due to the planned expansion to Thanet OWF which, given consent is granted, is expected to be fully commissioned in 2021 (Royal Haskoning, 2016). This would see a up to 34 turbines installed with a 340 MW capacity (Royal Haskoning, 2016).

Figure 30 Extent of the Thanet offshore wind farm development site. This figure was generated in QGIS version 2.18.13 using freely accessible OWF and bathymetry GIS data (EMODnet, 2018, 2015).

Pre-installation survey samples were taken using a 10 cm^2 mini-Hamon grab (Marine Ecological Surveys Ltd, 2008). It was found that sediments within the Thanet development site (TDS) were characterised by sand or gravelly sand (Marine Ecological Surveys Ltd, 2008). It was noted, however, that hard substrate was probably underestimated. Some grab samples could not be obtained due to hard substrate beneath a thin veil of fine sediments and this was not accounted for in the analysis (Marine Ecological Surveys Ltd, 2008). Megaripples trending east to west, with asymmetrical sand waves up to 3 m in height, characterised much of the sediment and indicated a predominantly southerly current (Gardline Geosurvey Ltd., 2012, 2007).

A major focus of the baseline surveys was *Sabellaria spinulosa*, which is a tube building polychaete. In dense concentrations, in regions with a good supply of suspended sand grains, *S. spinulosa* can build reef like structures at least several centimetres thick, stabilising cobble, pebble and gravel habitats (Maddock, 2008). *S. spinulosa* has been recorded in the Atlantic, North Sea, Mediterranean Sea and English Channel (Flavia et al., 2018; Pearce et al., 2014; “The national biodiversity network atlas,” n.d.; van der Reijden et al., 2019). However, *S. spinulosa* reefs are rare, with most located around the British coast (Benson et al., 2013; Gibb et al., 2014; Pearce et al., 2014; “The national biodiversity network atlas,” n.d.). *S. spinulosa* reefs are protected under Annex 1 of the EU Habitats Directive (European Commission, 2007; Marine Ecological Surveys Ltd, 2008; Thanet Offshore Wind Ltd, 2005), and included in the OSPAR list of threatened and/or declining habitats (OSPAR Commission, 2008) and the UK biodiversity action plan (BAP) priority habitats (Maddock, 2008). In the EIA it was reported that *S. spinulosa* in the southern part of the site had the potential to form biogenic reefs (Thanet Offshore Wind Ltd, 2005). Although the EIA highlighted potential risks to *S. spinulosa*, it was determined that appropriate placement of the turbines could mitigate this risk (Thanet Offshore Wind Ltd, 2005).

5.3.2 Artificial structures

Post-installation data were not available from turbines at Thanet OWF. However, epibenthic communities on offshore platforms are comparable with those on wind turbine foundations (Bouma, 2012; Causon and Gill, 2018; Forteath et al., 1982; Hiscock et al., 2002; Krone et al., 2013b; Southgate and Myers, 1985). It was therefore considered appropriate for community data from energy platforms in the southern North Sea (figure 31) to represent potential community compositions on turbine foundations.

The platforms sampled include 4 energy platforms, K9-A, L10-A, L10-G and L15-A, which are operated by ENGIE Exploration and Production Nederland B. V. (ENGIE), and the Fino 1 research platform. Fino 1 is an unmanned research platform located in German waters in the immediate vicinity of the Alpha Ventus OWF. All platforms are supported by steel jacket foundations in water depths between 22 and 32 metres (Anonymous, n.d.; Coolen et al., 2018). It should be noted that jacket foundations differ in structural characteristics from the monopiles that are most commonly used to support offshore wind turbines (figure 2).

The energy platforms were surveyed in 2014 by researchers from Wageningen University and Research (WUR). Fino 1 was surveyed between April and October from 2005 – 2007 by researchers from Alfred Wegener Institute (AWI). A detailed account of the platforms and the survey methodology is presented in chapter 3 (section 3.2). A combined total of 168 taxa recorded from surveys of the platform struts and scour protection layer were included in this assessment.

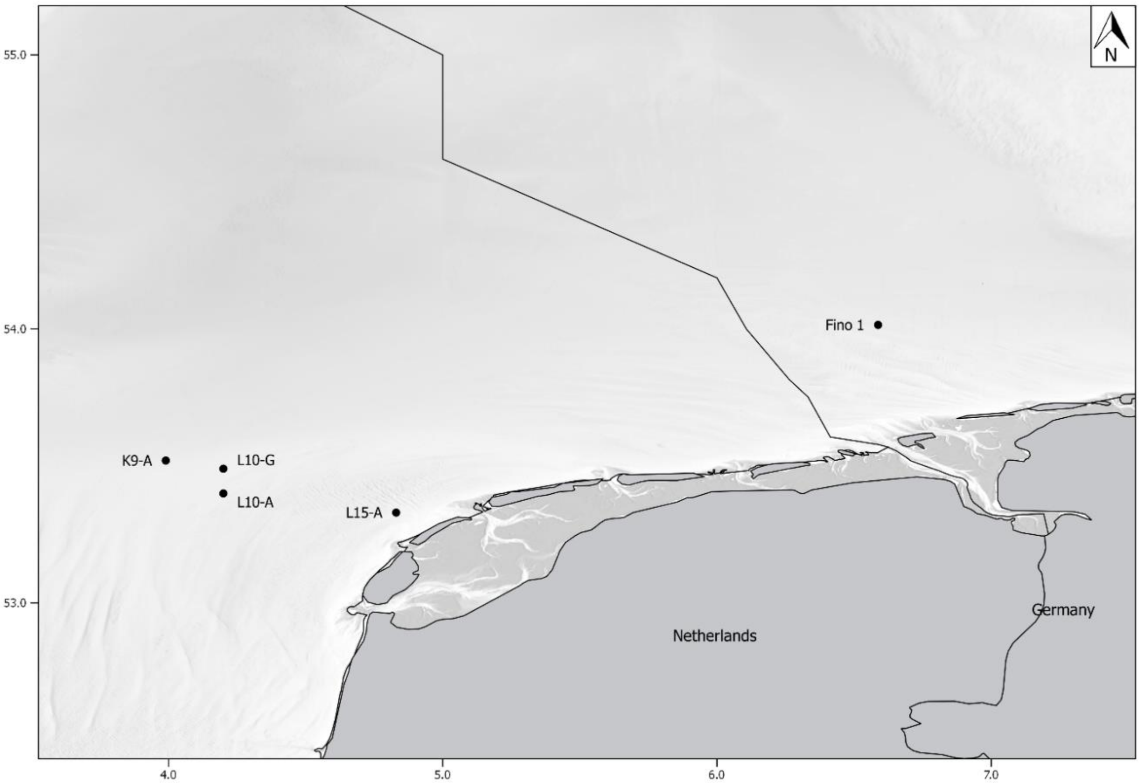

Figure 31 Map showing locations of platforms from which benthic community data was applied to the post-installation scenario. This figure was generated in QGIS version 2.18.13 using freely accessible OWF and bathymetry GIS data (EMODnet, 2018, 2015).

5.4 **Building the evidence base**

5.4.1 Asset register

A natural capital asset register forms the foundation of the NCA. The aim of the asset register is to provide an inventory of natural resources within a defined area in terms of quantity, quality and distribution (RSPB, 2017). The delivery of ecosystem services depends on the maintenance of those assets (figure 32).

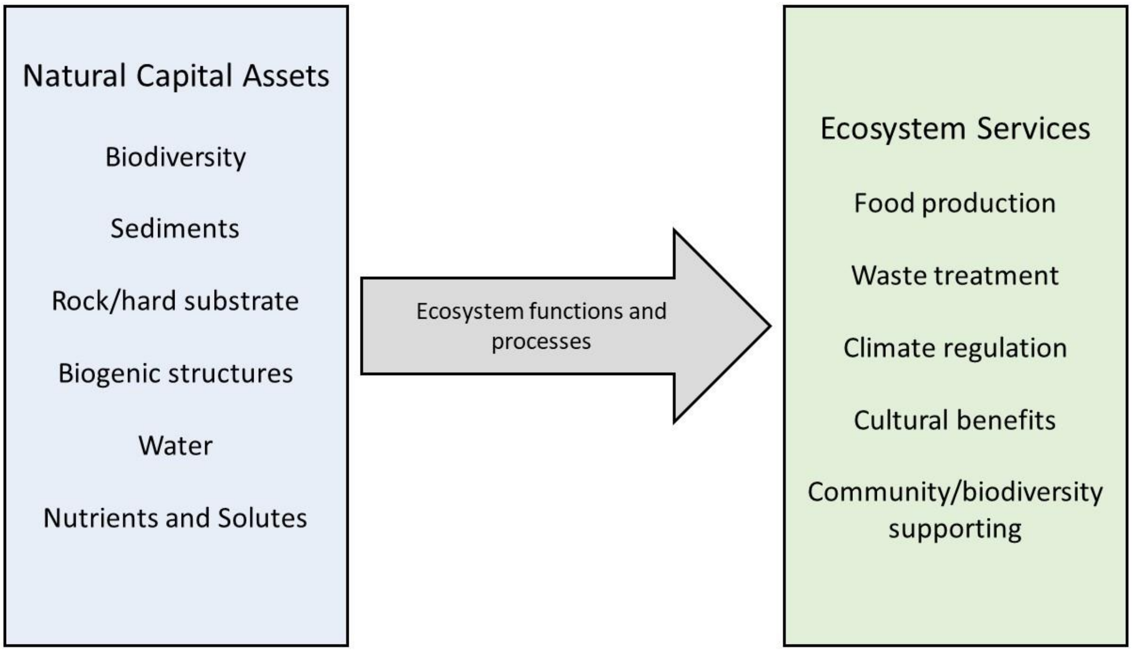

Figure 32 Illustration of ecosystem services (right box) generated from natural capital assets (left box) via functional pathways and natural processes..

Goods and benefits from nature essential to human life, are referred to as ecosystem services (Daily, 1997). They are typically categorised as provisioning (e.g. food), regulating (e.g. carbon sequestration), cultural (e.g. tourism) and supporting (e.g. nutrient cycling) (Reid et al., 2005). Ecosystem services occur at multiple spatial scales, for example carbon sequestration and climate regulation has a global effect whereas coastal protection and leisure benefits occur at local scales (Galparsoro et al., 2014). These services are products of natural processes and include functions performed by biota within ecosystems (Sandifer et al., 2015).

Soft sediments were the prevalent habitat type throughout the TDS. Typically, sediments ranged from sand to sandy gravel (figure 33). The BAP identifies subtidal sands and gravels as a priority habitat (Maddock, 2008).

A total of 166 taxa from the 2005 and 2007 benthic biological resource surveys were included in this assessment (table 11). In addition to several polychaetes, the bivalve *Abra alba* and the decapod *Pisidia longicornis* were particularly abundant (469 and 181 respectively). Species within the phyla Bryzoa and Entoprocta, as well as those in the class Hydrozoa, were not recorded in terms of abundance. These species are typically colonial and were recorded only as present (P).

Polychaetes dominated soft sediments, with 83 identified taxa (table 11), including *Sabellaria spinulosa* and *Lanice conchilega* (figure 34) (Marine Ecological Surveys Ltd, 2008). By constructing tubes, *S. spinulosa* and *L. conchilega* can develop biogenic reefs (Coates et al., 2011; De Smet et al., 2015; Flavia et al., 2018; Hendrick and Foster-Smith, 2006; Van Hoey et al., 2008). In doing so, they stabilise sediments and increase habitat complexity, which provides opportunities for food and shelter (De Smet et al., 2013; Degraer et al., 2008; Maddock, 2008; Petersen and Exo, 1999; Rabaut et al., 2013). Typically, dense beds of *L. conchilega* rise 10-40 cm from the seabed due to sediment trapping between tubes (Hild and Günther, 1999).

S. spinulosa reefs that occur in sediment or mixed sediment habitats are of greatest conservation concern (Maddock, 2008). The reefs can persist for many years and may be older than the oldest members of the community (Maddock, 2008) and support diverse benthic communities. Indeed, anemones (*Sagartia spp.*) and hydroids (*Obelia spp.* and *Halecium spp.*) have been recorded in higher abundance within *S. spinulosa* reefs than in sedimentary habitats (Pearce et al., 2014). In addition, motile species such as the common starfish (*Asterias rubens*), and the long-clawed porcelain crab, *Pisidia longicornis*, have been found in greater abundance on *S. spinulosa* reefs than in adjacent sedimentary habitats (Pearce et al., 2014).

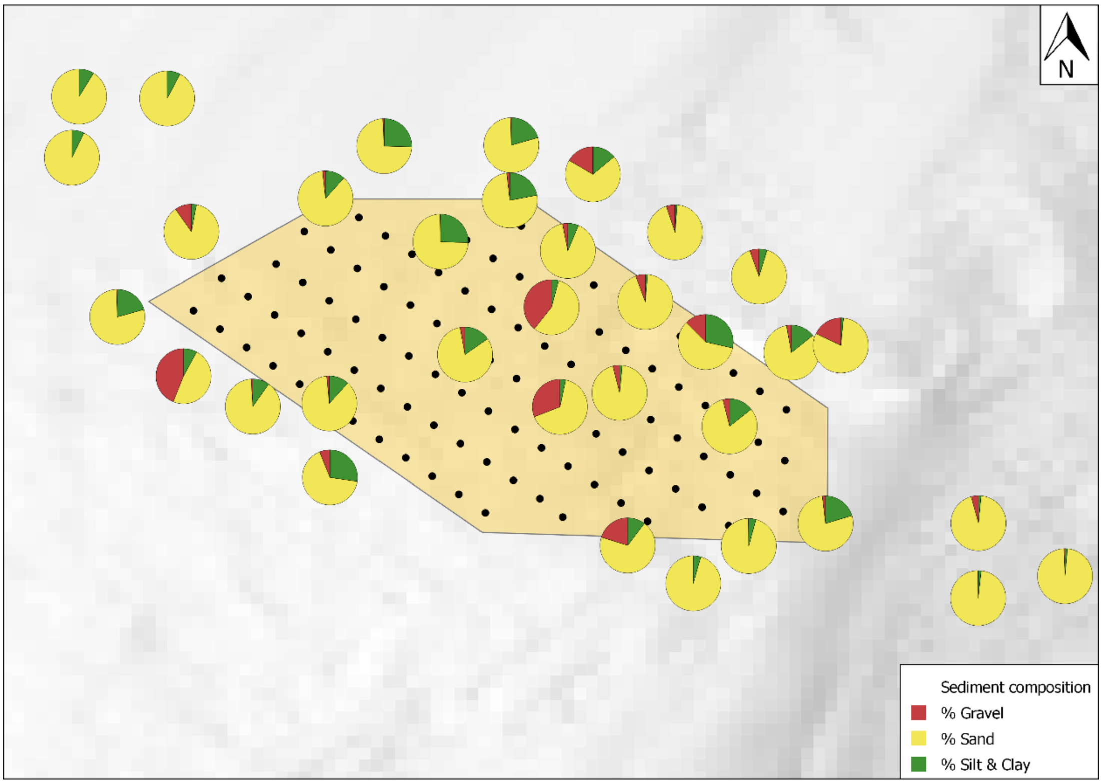

Figure 33 Pie charts show sediment composition within and close to the Thanet wind farm extent prior to installation. Black dots show the locations of wind turbines following installation. This figure was generated in QGIS version 2.18.13 using freely accessible OWF and bathymetry GIS data (EMODnet, 2018, 2015; Kis-orca, 2015) and turbine positions from (Pearce et al., 2014).

Colonies of *S. spinulosa* were found in highest densities (up to 665 individuals) in the southern part of the site (figure 34). High resolution acoustic surveys, using side-scan sonar and multibeam echosounder, were conducted in 2005 and 2007 (prior to the OWF installation), and in 2012 (following the OWF installation) (Pearce et al., 2014). The 2005 survey was concentrated to the south of the TDS as *S. spinulosa* records from baseline samples were constrained to this area (Pearce et al., 2014). Yet, in the 2007 and 2012 acoustic surveys *S. spinulosa* reefs were identified in the north of the TDS as well (Pearce et al., 2014). The 3 surveys showed considerable variability in the extent of *S. spinulosa* reefs. In the southern sector, reefs were found to cover an area of 2.57 km^2, but the

2007 and 2012 surveys put measured an area of 0.48 km^2 and 0.90 km^2 in the same area (Pearce et al., 2014). Over the entire site, *S. spinulosa* reefs covered an area of 2.59 km^2 in 2007 and 2.91 km^2 in 2012 (Pearce et al., 2014) which represents 7.4% and 8.3% of the area respectively.

During base line sampling *L. conchilega* was recorded in highest densities (up to 33 individuals per 10 cm^2) outside of the wind farm extent, to the West (figure 34). However, as acoustic surveys targeted *S. spinulosa* and it is not known whether *L. conchilega* reefs occurred within the TDS.

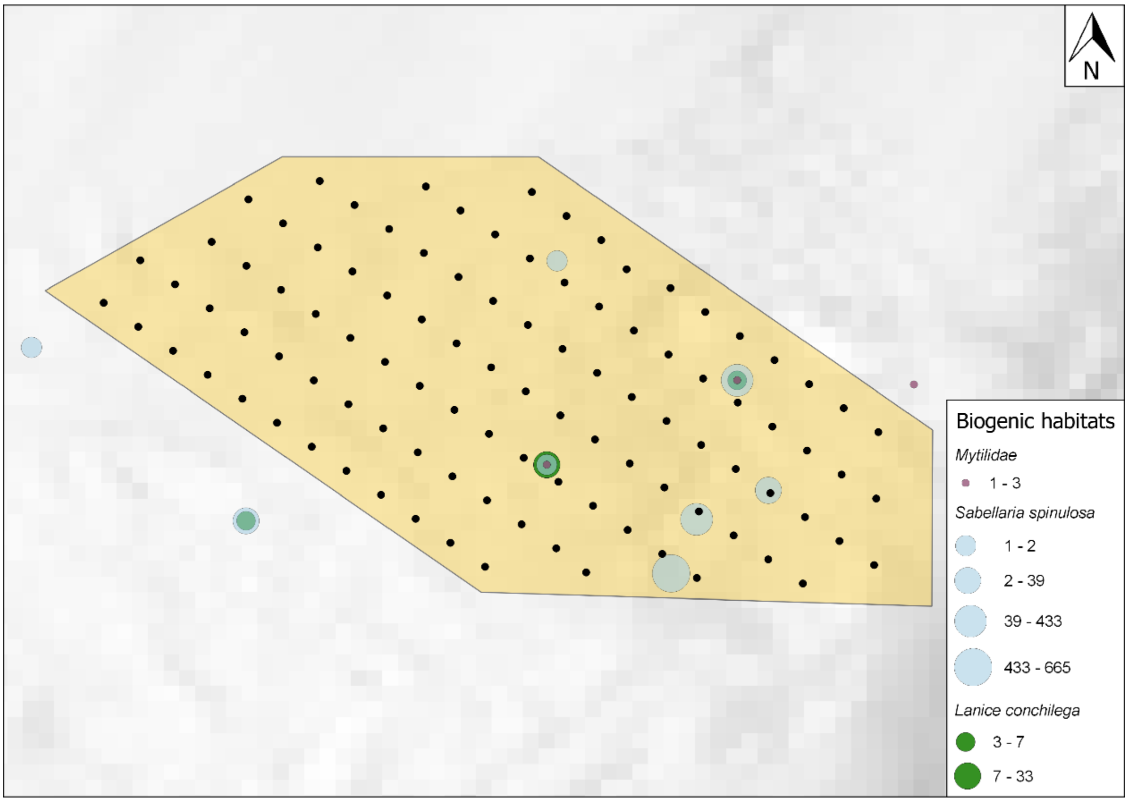

Figure 34 Locations and abundance (number of individuals per 10 cm^2) of reef building taxa from pre-installation survey samples. Black dots show the locations of wind turbines following installation (not to scale). This figure was generated in QGIS version 2.18.13 using freely accessible OWF and bathymetry GIS data (EMODnet, 2018, 2015; Kis-orca, 2015) and turbine positions from (Pearce et al., 2014).

Blue mussel (*Mytilus edulis*) beds on sediment are another BAP habitat that have previously been identified in the TDS, although it only occupied a small area (Pearce et al., 2014). Mussel aggregations have a role in sediment dynamics and provide food, refuge and substrate for attachment for diverse benthic communities (Maddock, 2008). However, during the Thanet OWF pre-installation surveys the majority of mussels were recorded at the family level (Mytilidae) (figure 34) and were recorded in low abundance and in few samples. Thus, the true coverage of *M. edulis* beds in the area is uncertain.

Once the Thanet OWF was completed a total 100 offshore wind turbines were installed. They were built on monopiles with a diameter of 4.1 to 4.9 m, with no scour protection (Vattenfall Wind Power Ltd, 2017a). It can therefore be estimated that the monopiles covered approximately 0.001 to 0.002 km^2 of the TDS. It can be conservatively estimated, based on a minimum monopile diameter of 4.1 m and installed depth range of 15 m, that the turbines within Thanet would provide at least approximately 0.02 km^2 of surface area. This equates to approximately 20 times the area lost from the placement of the OWF.

The substructures provide hard substrate that is expected to be colonised by epibenthic marine biota. In chapter 3, a permutational analysis of variance (PERMANOVA) was used to compare differences in community composition between natural rock reefs, soft sediment sites, including those at Thanet, and the 5 artificial platforms included here. Significant differences ($P \leq 0.01$) were found in community structure between the pre-installation Thanet site and all platforms. Therefore, it is assumed that there will be a change in natural capital, at least at the local scale, following the installation of the Thanet wind farm.

Based on epibenthic community data from artificial platforms, a total of 181 taxa from artificial structures were included in this assessment (table 11). Abundance is available for most taxa, but as with the soft sediment samples from the Thanet site, some hydrozoans and Bryozoans were recorded only as present. Samples from the artificial structures were also dominated by polychaetes, however there were half as many polychaete families/species present compared to the soft sediment, with 41 (mean = 0.2) and 82 taxa (mean = 0.4) respectively. Although those taxa present showed greater abundance compared to soft sediment taxa. For example, mean abundance of *S. spinulosa* recorded on platforms was 775 individuals per 5 cm^2, whereas a mean of around 34 individuals per 10 cm^2 was recorded from soft sediments at the Thanet site. Similarly, a mean abundance of around 63 individuals per 5 cm^2 for *L. conchilega* from platforms compared with <2 individuals per 10 cm^2 in soft sediments prior to the OWF installation.

The number of families/species present on platforms exceeded those on soft sediments for the majority of taxa. For instance, this trend was observed for all Cnidaria and Mollusca, as well as Bryozoans in the class Gymnolaemata and Arthropods of the class Decapoda.

Mean abundance of Mytilidae recorded on the platforms also far exceeded Mytilidae recorded in soft sediments in the Thanet site (2997.8 and 0.4 respectively). On the platforms, Mytilidae was comprised of *M. edulis* only. It should be noted however that, despite this increase, BAP habitat only covers 'natural' beds on a variety of sediment types (Maddock, 2008). Thus, mussel beds on artificial substrate, rocks and boulders are excluded. This notwithstanding, the increased presence of these taxa would contribute to ecosystem functioning and services.

Table 11 Total and mean abundance of taxa recorded in 33 samples from soft sediment (prior to the installation of Thanet OWF) and 255 samples from platform substructures (representative of communities on monopiles in Thanet OWF). Under total, P = present and A = absent. Due to the zero inflated data, standard deviations exceeded the value of the mean which would imply negative abundance. As such the standard deviations have not been reported.

Taxa	Pre-OWF installation		Post-OWF installation	
	Total	**Mean**	**Total**	**Mean**
Annelida				
Oligochaeta				
Grania spp.	5	0.1	0	0
Naididae	22	0.6	0	0
Polychaeta				
Aphroditiformia	0	0	1	0.2
Amaeana trilobata	1	<0.1	0	0
Ampharete lindstroemi	8	0.2	0	0

Aonides oxycephala	7	0.2	0	0
Aonides paucibranchiata	9	0.3	0	0
Aphelochaeta marioni	2	0.1	0	0
Aricidea minuta	17	0.5	0	0
Capitella spp.	0	0	4	0.8
Caulleriella alata	107	3.1	0	0
Chaetopterus variopedatus	0	0	2	0.4
Chaetozone zetlandica	15	0.4	0	0
Chama pulchella	1	0	0	0
Crucigera spp.	0	0	1	0.2
Dipolydora caulleryi	1	<0.1	0	0
Dipolydora coeca	3	0.1	0	0
Echiuridae	1	0	0	0
Eteone flava	3	0.1	0	0
Eteone longa	4	0.1	0	0
Eulalia clavigera	0	0	3	0.6
Eulalia ornata	4	0.1	0	0
Eulalia viridis	1	<0.1	568	113.6
Eumida spp.	44	1.3	1	0.2
Eunereis longissima	6	0.2	438	87.6
Eusyllis blomstrandi	5	0.1	373	74.6
Exogone naidina	3	0.1	0	0
Exogone verugera	1	<0.1	0	0
Gattyana cirrhosa	0	0	1	0.2
Glycera spp.	48	1.4	4	0.8
Goniada maculata	38	1.1	0	0
Harmothoe spp.	83	2.4	238	47.6
Hesionura elongata	28	0.8	0	0
Hilbigneris gracilis	176	5.0	0	0
Jasmineira elegans	18	0.5	0	0
Lagis koreni	8	0.2	0	0
Lanice conchilega	49	1.4	316	63.2
Lepidonotus squamatus	4	0.1	97	19.4
Lumbrineridae	0	0	24	4.8
Magelona mirabilis	33	0.9	0	0
Maldanidae	2	0.1	0	0
Malmgrenia arenicolae	7	0.2	0	0
Malmgrenia marphysae	2	0.1	0	0
Marphysa sanguinea	5	0.1	0	0
Mediomastus fragilis	98	2.8	0	0
Microphthalmus similis	11	0.3	0	0
Microspio mecznikowianus	5	0.1	0	0
Myrianida spp.	1	<0.1	13	2.6
Mysta picta	3	0.1	0	0
Neogyptis rosea	2	0.1	0	0

Nephtys caeca	32	0.9	0	0
Nephtys hombergii	31	0.9	0	0
Nereis spp.	0	0	179	35.8
Nothria conchylega	0	0	10	2.0
Notomastus latericeus	327	9.3	18	3.6
Ophelia borealis	224	6.4	0	0
Owenia fusiformis	3	0.1	0	0
Paranaitis kosteriensis	3	0.1	0	0
Paraonis fulgens	18	0.5	0	0
Pectinaria	0	0	1	0.2
Pherusa plumosa	1	<0.1	0	0
Pholoe baltica	17	0.5	0	0
Pholoe inornata	4	0.1	0	0
Phyllodoce groenlandica	0	0	3	0.6
Phyllodoce longipes	1	<0.1	2	0.4
Phyllodoce maculata	7	0.2	1	0.2
Phyllodoce mucosa	0	0	24	4.8
Pisione remota	11	0.3	0	0
Podarkeopsis capensis	5	0.1	0	0
Poecilochaetus serpens	10	0.3	0	0
Polycirrus medusa	7	0.2	0	0
Polydora ciliata	0	0	1	0.2
Polynoidae	1	<0.1	0	0
Praxillella affinis	3	0.1	0	0
Proceraea cornuta	0	0	5	1.0
Proceraea prismatica	8	0.2	0	0
Protodorvillea kefersteini	7	0.2	0	0
Psamathe fusca	28	0.8	0	0
Pseudopotamilla reniformis	1	<0.1	0	0
Sabellaria spinulosa	1201	34.3	3875	775.0
Sabellidae	0	0	1	0.2
Saccocirrus papillocercus	36	1.0	0	0
Scalibregma inflatum	122	3.5	0	0
Schistomeringos neglecta	3	0.1	0	0
Sclerocheilus minutus	3	0.1	0	0
Scolelepis bonnieri	4	0.1	0	0
Scoloplos armiger	9	0.3	0	0
Sphaerodorum gracilis	1	<0.1	0	0
Spio filicornis	2	0.1	0	0
Spio martinensis	1	<0.1	0	0
Spiophanes bombyx	58	1.7	0	0
Spirobranchus lamarcki	8	0.2	0	0
Spirobranchus triqueter	0	0	1	0.2
Spirorbis spirorbis	0	0	2	0.4
Sthenelais boa	5	0.1	4	0.8

Subadyte pellucida	0	0	1	0.2
Syllidia armata	1	<0.1	0	0
Syllis armillaris	0	0	50	10
Syllis gracilis	0	0	19	3.8
Syllis hyalina	3	0.1	1	0.2
Syllis variegata	1	<0.1	0	0
Terebellides stroemii	1	<0.1	0	0
Thelepus cincinnatus	1	<0.1	0	0
Arthropoda				
Copopoda	0	0	654	130.8
Decapoda				
Atelecyclus spp.	0	0	6	1.2
Anapagurus laevis	2	0.1	0	0
Cancer pagurus	0	0	100	20
Carcininae	0	0	6	1.2
Crangon crangon	1	0	0	0
Ebalia tuberosa	3	0.1	0	0
Eualus cranchii	0	0	2	0.4
Eualus occultus	1	0	0	0
Galathea intermedia	0	0	2	0.4
Hippolyte varians	0	0	2	0.4
Liocarcinus depurator	0	0	9	1.8
Liocarcinus holsatus	0	0	6	1.2
Liocarcinus navigator	0	0	1	0.2
Liocarcinus pusillus	1	<0.1	0	0
Majoidea	0	0	1	0.2
Paguridae	0	0	1	0.2
Pagurus bernhardus	6	0.2	0	0
Pilumnus hirtellus	3	0.1	14	2.8
Pilumnus spinifer	0	0	1	0.2
Pinnotheres pisum	0	0	3	0.6
Pisidia longicornis	181	5.2	1317	263.4
Portunidae	0	0	16	3.2
Hexanauplia				
Cirripedia	0	0	2	0.4
Hexapoda				
Telmatogeton japonicus	0	0	72	14.4
Isopoda				
Idotea pelagica	0	0	1116	223.2
Ostracoda	6	0.2	0	0
Peracarida				
Abludomelita obtusata	6	0.2	5	1.0
Ampelisca diadema	1	<0.1	0	0
Ampelisca spinipes	1	<0.1	0	0
Amphilochus manudens	2	0.1	0	0

Aora gracilis	4	0.1	3	0.6
Apocorophium lacustre	0	0	239	47.8
Bathyporeia pelagica	5	0.1	0	0
Bathyporeia pilosa	15	0.4	0	0
Bathyporeia sarsi	28	0.8	0	0
Bathyporeia tenuipes	1	<0.1	0	0
Bodotria scorpioides	3	0.1	0	0
Caprella linearis	0	0	132	26.4
Chelicorophium curvispinum	0	0	2	0.4
Cumacea	0	0	48	9.6
Diastylis bradyi	1	<0.1	0	0
Diastylis rathkei	1	<0.1	0	0
Diastylis rugosa	1	<0.1	0	0
Dyopedos monacanthus	28	0.8	0	0
Ericthonius brasiliensis	4	0.1	0	0
Gammaridea	0	0	10752	2150.4
Gammaropsis maculata	19	0.5	0	0
Gastrosaccus spinifer	2	0.1	0	0
Gitana sarsi	0	0	167	33.4
Jassa herdmani	0	0	190534	38106.8
Jassa marmorata	0	0	10108	2021.6
Lysianassa ceratina	2	0.1	0	0
Maerella tenuimana	1	<0.1	0	0
Metopa borealis	3	0.1	1	0.2
Metopa bruzelii	0	0	1	0.2
Metopa pusilla	0	0	9128	1825.6
Microprotopus maculatus	0	0	571	114.2
Monocorophium acherusicum	0	0	95	19.0
Monocorophium insidiosum	0	0	32	6.4
Monocorophium sextonae	87	2.5	2655	531.0
Mysida	0	0	128	25.6
Nototropis swammerdamei	0	0	5	1.0
Phtisica marina	0	0	4231	846.2
Podoceridae	1	0	0	0
Siriella spp.	1	0	0	0
Socarnes erythrophthalmus	3	0.1	0	0
Stenothoe marina	48	1.4	28	5.6
Stenothoe monoculoides	0	0	2506	501.2
Stenothoe tergestina	0	0	2	0.4
Stenothoe valida	0	0	556	111.2
Stenula solsbergi	0	0	11	2.2
Synchelidium intermedium	2	0.1	0	0
Tryphosa nana	0	0	1	0.2
Urothoe brevicornis	49	1.4	0	0
Urothoe elegans	1	<0.1	0	0

Sessilia				
Balanus balanus	0	0	451	90.2
Balanus crenatus	31	0.9	341	68.2
Balanus improvisus	0	0	1	0.2
Perforatus perforatus	0	0	2	0.4
Semibalanus balanoides	0	0	1	0.2
Verruca stroemia	0	0	4	0.8
Bryozoa				
Gymnolaemata				
Aetea anguina	0	0	2	0.4
Alcyonidioides mytili	0	0	4	0.8
Alcyonidium condylocinereum	0	0	1	0.2
Alcyonidium diaphanum	P		A	
Alcyonidium parasiticum	0	0	2	0.4
Amathia spp.	0	0	2	0.4
Arachnidium fibrosum	0	0	13	2.6
Aspidelectra melolontha	A		P	
Bicellariella spp.	P		P	
Bugulina turbinata	A		P	
Buskia nitens	0	0	1	0.2
Callopora dumerilii	0	0	7	1.4
Celleporella hyalina	0	0	3	0.6
Conopeum reticulum	0	0	4	0.8
Cribrilina spp.	0	0	1	0.2
Electra monostachys	A		P	
Electra pilosa	P		P	
Escharella spp.	A		P	
Microporella ciliata	0	0	2	0.4
Schizomavella (Schizomavella) linearis	0	0	1	0.2
Scruparia ambigua	0	0	3	0.6
Scruparia chelata	0	0	3	0.6
Scrupocellaria scruposa	P		A	
Stenolaemata				
Crisia eburnea	P		A	
Cephalorhyncha				
Priapulida	0	0	1	0.2
Chaetognatha				
Parasagitta spp.	1	<0.1	0	0
Chlorophyta	0	0	2	0.4
Chordata				
Ascidiacea				
Diplosoma listerianum	0	0	6	1.2
Ascidia conchilega	5	0.1	0	0
Molgulidae	0	0	104	20.8
Ciliophora	0	0	1	0.2

Cnidaria				
Anthozoa				
Actinothoe sphyrodeta	0	0	357	71.4
Actinaria	62	1.8	0	0
Alcyonium digitatum	0	0	11	2.2
Corynactis viridis	0	0	459	91.8
Diadumene cincta	0	0	1489	297.8
Diadumene lineata	0	0	1	0.2
Metridium dianthus	0	0	2652	530.4
Sagartia elegans	0	0	228	45.6
Urticina spp.	0	0	138	27.6
Hydrozoa				
Bougainvilliidae	P		P	
Calycella syringa	A		P	
Clytia spp.	P		P	
Corymorphidae	A		P	
Coryne spp.	A		P	
Ectopleura spp.	0	0	2	0.4
Eudendrium spp.	A		P	
Gonothyraea loveni	A		P	
Hartlaubella gelatinosa	0	0	1	0.2
Hydractinia echinata	P		P	
Laomedea calceolifera	0	0	1	0.2
Laomedea flexuosa	0	0	*2*	0.4
Laomedea neglecta	0	0	1	0.2
Obelia spp.	P		P	
Sertularia cupressina	P		P	
Tubulariidae	P		P	
Echinodermata				
Asteroidea				
Asterias rubens	0	0	643	128.6
Echinoidea				
Psammechinus miliaris	0	0	46	9.2
Echinocardium cordatum	6	0.2	0	0
Holothuroidea				
Leptosynapta inhaerens	5	0.1	0	0
Ophiuroidea				
Amphipholis squamata	11	0.3	370	74.0
Ophiothrix fragilis	1	<0.1	135	27.0
Ophiura spp.	92	2.6	0	0
Entoprocta				
Pedicellina nutans	P		P	
Mollusca				
Bivalvia				

Abra spp.	0	0	3	0.6
Abra alba	469	13.4	0	0
Abra nitida	1	<0.1	0	0
Abra prismatica	2	0.1	0	0
Aequipecten opercularis	0	0	1	0.2
Anomia ephippium	0	0	1	0.2
Buccinoidea	0	0	1	0.2
Corbula gibba	3	0.1	2	0.4
Fabulina fabula	2	0.1	0	0
Heteranomia squamula	0	0	39	7.8
Hiatella arctica	6	0.2	24	4.8
Kurtiella bidentata	25	0.7	8	1.6
Lepton squamosum	0	0	3	0.6
Musculus subpictus	2	0.1	1	0.2
Mytilidae	14	0.4	14989	2997.8
Nucula spp.	3	0.1	2	0.4
Ostreidae	0	0	16	3.2
Phaxas pellucidus	2	0.1	0	0
Spisula elliptica	13	0.4	0	0
Tellimya ferruginosa	6	0.2	0	0
Tellinidae	0	0	17	3.4
Veneridae	0	0	3	0.6
Gastropoda				
Acanthodoris pilosa	0	0	1	0.2
Adalaria proxima	0	0	2	0.4
Aeolidia papillosa	0	0	72	14.4
Aeolidiella glauca	0	0	25	5.0
Brachystomia scalaris	0	0	542	108.4
Catriona gymnota	0	0	7	1.4
Coryphella spp.	0	0	8	1.6
Dendronotus frondosus	2	0.1	1	0.2
Dorididae	0	0	3	0.6
Doto spp.	3	0.1	0	0
Epitonium clathrus	0	0	4	0.8
Eubranchus spp.	6	0.2	7	1.4
Euspira spp.	8	0.2	2	0.4
Flabellinidae	0	0	2	0.4
Neogastropoda	0	0	1	0.2
Onchidoris bilamellata	0	0	3	0.6
Polycera spp.	0	0	5	1.0
Pyramidellidae spp.	0	0	98	19.6
Sacoglossa	1	<0.1	0	0
Spiralinella spiralis	5	0.1	0	0
Tergipedidae	0	0	3	0.6
Tergipes tergipes	0	0	15	3.0

Tritia reticulata	3	0.1	0	0
Tritonia spp.	0	0	1	0.2
Nematoda	22	0.6	0	0
Nemertea	140	3.8	82	16.4
Ochrophyta				
Phaeophyceae	0	0	2	0.4
Phoronida				
Phoronis spp.	1	<0.1	0	0
Platyhelminthes	0	0	2	0.4
Porifera	0	0	19	3.8
Rhodophyta	0	0	3	0.6
Sipuncula				
Golfingia vulgaris	1	<0.1	0	0
Nephasoma minutum	4	0.1	0	0

Based on the available information, prior to the installation of Thanet OWF, the development area was characterised by soft sediment, which consisted predominantly of sand with varying degrees of gravel, silt and clay. Soft sediment may have accounted for up to 93% of habitat in the TDS. *S. spinulosa* reefs were found to cover around 7% of the area prior to the installation of the OWF. Although, it is likely that this is an underestimate of the coverage of biogenic reefs. A small area of mussel beds were identified, but its extent was not reported (Pearce et al., 2014). In addition, *L. conchilega* was recorded in grab samples, although in relatively low abundance. It is unknown if *L. conchilega* reefs existed in the area prior to installation.

Following the installation of the Thanet OWF, wind turbines covered 0.02% of the area, slightly reducing soft sediment habitat by creating a substantial amount of hard substrate. Thus, the wind turbines increase the heterogeneity of the habitat as it changes from a largely flat, planer environment to one with large 3-dimensional structures throughout. This represents a significant change to the composition of the habitat.

S. spinulosa reefs increased, covering roughly 8% of the TDS. Although, as mentioned, this may be an underestimate. Thus, soft sediment habitat covered approximately 92% of the TDS. Also, table 11 suggests that there would be an increase species richness and biomass following the installation of the turbines. A total of 140 species occurred on the artificial platforms that were absent from the soft sediments. Some with an average abundance of hundreds (e.g. *Diadumene cincta*, *Metridium dianthus*, *Balanus balanus* and *Asterias rubens*) or thousands (e.g. *Jassa herdmani*, *J. marmorata*, *Metopa pusilla* and Gammaridae spp.) of individuals per sample. Other taxa, including Mytilidae and *L. conchilega*, were considerably more abundant in platforms samples than soft sediment samples. Therefore, the installation of the OWF is expected to lead to an increase in natural capital close to the turbines and across the scale of the OWF.

5.4.2 Flow of benefits and ecosystem services

A major benefit provided by OWFs is the generation of low carbon energy when compared with other forms of energy production. It has been estimated that average life cycle emissions of offshore wind energy are 16 gCO_2/kWh_e (Kaldellis and Apostolou, 2017). This takes in to consideration all stages of construction, operation and maintenance, and decommissioning (including raw material extraction, processing, transport and fuel consumption, and end-of-life recycling credit). Estimates of average life cycle CO_2 emissions for competing energy production technologies include hydro (28 gCO_2/kWh_e), nuclear (33 gCO_2/kWh_e), solar photovoltaic (75 gCO_2/kWh_e), natural gas fired (450 gCO_2/kWh_e), oil fired (840 gCO_2/kWh_e) and coal fired (1050 gCO_2/kWh_e) (Kaldellis and Apostolou, 2017). In addition, comparisons of the life cycle emissions of air pollutants such as NO_x, SO_2 and particles indicate a good performance for wind power (offshore and onshore) against other forms of energy production (Edenhofer et al., 2012).

For an OWF most of the CO_2 emissions, approximately 80%, are released during the construction phase (Kaldellis and Apostolou, 2017). Operation and maintenance over the life of the OWF accounts for between 5-20%, with decommissioning and other undefined activities encompassing the remaining $\leq$15% of CO_2 emissions (Kaldellis and Apostolou, 2017).

Although coastal ecosystems cover around 8% of the earth's surface, it has been estimated that they contribute 43% of the total value of ecosystem services (Costanza et al., 1997). Given the installation of the multiple turbines, including substructures and scour protection, the resulting modification to the habitat from an OWF may influence the delivery of ecosystem services (Causon and Gill, 2018).

Modification of the habitat by the OWF is expected to result in benefits related to ecological changes. Table 12 illustrates the flow of ecosystem services delivered by soft sediments and biogenic reefs at the Thanet site prior to the OWF installation. For example, in terms of food provision, a small fishing fleet was reported to operate out of Ramsgate, which mainly performed gill net fishing, with nets anchored to the seabed or set to drift with the currents (Thanet Offshore Wind Ltd, 2005). In addition, some larger vessels from further afield in the UK and the EU have been active in the region, including trawlers from Belgium and Holland (Marine Ecological Surveys Ltd, 2008; Thanet Offshore Wind Ltd, 2005). The Thanet area supports a number of fish species, with lesser-spotted dogfish (*Scyliorhinus canicula*), dab (*Limanda limanda*), Dover sole (*Solea solea*), smooth hound (*Mustelus mustelus*) and thornback ray (*Raja clavata*) commonly caught by fisherman (Walker et al., 2009).

S. spinulosa reefs and mussel beds located within the Thanet development site (Pearce et al., 2014) are likely to support local fisheries by providing refuge and feeding grounds. Although *L. conchilega* reefs were not specifically identified, individuals were recorded in pre-construction samples (figure 34). Therefore, *L. conchilega* reefs may also exist in the area, stabilising sediments and generating habitat that supports fisheries.

Benthic invertebrates have an important role in supporting biodiversity and productivity. Bioturbation of sediments, through burrowing, tube building, feeding and ventilation activities, transfer organic matter in to sediments and influence the rates of remineralisation and inorganic nutrient efflux (Aller, 1994, 1988; Christensen et al., 2000; Hansen and Kristensen, 1997; Kristensen, 2000; Lohrer et al., 2004; Sandnes et al., 2000; Welsh, 2010; Yingst and Rhoads, 1980). Inorganic matter returned to the water column by bioturbating organisms influences primary productivity. *L. conchilega* has been shown to transport oxygen-rich water deep in to sediments effecting benthic respiration, nutrient release and denitrification (Braeckman et al., 2010; Forster and Graf, 1995).

Suspension feeders, such as *M. edulis* and *S. spinulosa*, remove particulate matter from the water column. The potential for dense colonies of mussels to improve water quality has frequently been reported (Hooper et al., 2017b; Lange et al., 2010; Lindahl et al., 2005). A similar phenomenon has been noted in Serpulid polychaetes and large *S. spinulosa* reefs, although in the case of the latter the effect is likely to be minimal and localised in open sublittoral communities (Pearce et al., 2011).

Table 12 Natural capital assets and corresponding ecosystem services before and after the OWF installation

Pre-OWF installation			Post-OWF installation		
Natural capital assets	**Ecosystem service**	**Source**	**Natural capital assets**	**Ecosystem service**	**Source**
			Provisioning		
Biodiversity, nutrients and solutes, water	Gill net fishing and trawling reported within the region	Marine Ecological Surveys Ltd, 2008; Thanet Offshore Wind Ltd, 2005	OWF	Some displacement of local fishing activity expected. Exclusion of fishing may support the recovery of stocks.	Thanet Offshore Wind Ltd, 2005; Coates et al., 2016; Lindeboom et al., 2011
Biogenic structures	*S. spinulosa* reefs and mussel beds generate habitat, providing opportunities for feeding and shelter for commercial species.	Holt et al., 1998; Pearce et al., 2011; Salomidi et al., 2012	Hard substrate, Biodiversity	Turbine substructures and sessile epibenthic communities provide food and shelter for adults and juveniles, supporting stocks of commercially exploited species.	Fayram and Risi, 2007; Hooper et al., 2017a; Mangi, 2013; Petersen and Malm, 2006; Reubens et al., 2011; Wilhelmsson et al., 2006
			Hard substrate, Biodiversity	Some colonisers, such as mussels, are potentially harvestable for human consumption.	Hooper et al., 2017a
			Biogenic structures	Recovery and increase in *S. spinulosa* reefs and mussel bed. Greater extent of habitat providing opportunities for feeding and shelter for commercial species.	Holt et al., 1998; Pearce et al., 2011; Salomidi et al., 2012

Regulating					
Biodiversity	CO_2 sequestration: Inorganic carbon dissolved in to seawater is converted to organic carbon by photosynthetic phytoplankton and algae in water column.	Liquete et al., 2013	Hard substrate, Biodiversity	Increased Carbon sequestration due to greater biomass on or around the turbine.	Alonso et al., 2012; Burrows et al., 2014; Hooper et al., 2017a; Lange et al., 2010
Biodiversity and biogenic structures	Water quality: Suspension feeding, particularly in mussel beds, but also *S. spinulosa* reefs and Serpulid polychaetes, is likely to improve water quality.	Davies et al., 1989; Pearce et al., 2011	Biodiversity	Increased biomass of some bacteria, algae, crabs and mussels on or near turbines is likely to improve water quality and remediate waste and toxins, such as heavy metals.	Hooper et al., 2017a; Iyer et al., 2005; Lange et al., 2010; Mangi, 2013
Biogenic structures	*S. spinulosa* reefs have been shown to increase biodiversity. There is a body of evidence that suggests high biodiversity and ecosystem stability decreases the rate of successful invasions by non-native species. This is likely due to low niche availability.	Pearce et al., 2011	Biodiversity	Deposition of organic matter from sessile epibenthic communities' influences transfer of organic matter to sediments.	Coates et al., 2011, 2014; Maar et al., 2009

Biogenic structures	Large *S. spinulosa* reefs likely to have a role in Carbon cycling	Pearce et al., 2011	Hard substrate	OWFs may serve as nursery grounds.	Bunker, 2004; Hooper et al., 2017a; Leonhard and Pedersen, 2005; Reubens et al., 2013
			Biogenic structures	Recovery and increase *S. spinulosa* reefs. Likely to promote further biodiversity and Carbon cycling. The recovery of biogenic reefs is also likely to stabilise sediments	De Smet et al., 2013; Degraer et al., 2008; Maddock, 2008; Petersen and Exo, 1999; Rabaut et al., 2013
Supporting					
Biogenic reefs	Nutrient and energy cycling in biogenic reefs and mussel beds.	Pearce et al., 2011	Biodiversity	Increase in mussel biomass may significantly reduce local phytoplankton concentrations in the water column through filter feeding.	Burkhard et al., 2011; Dolmer, 2000; Maar et al., 2009
Sediments and biodiversity	Nutrient and energy cycling in sediment layers by infaunal deposit and suspension feeding and bioturbation transports organic matter and dissolved materials between the sediment and the water column. In doing so they raise productivity and support biodiversity.	Bertics et al., 2010; Ganeshram et al., 2002; Jørgensen, 1996; Laverock et al., 2011; Riisgård et al., 1996; Welsh, 2010	Biogenic reefs	Recovery of biogenic reefs and mussel beds could further promote nutrient and energy cycling in the extent of the wind farm.	Pearce et al., 2011

Cultural					
Biodiversity, water and nutrients	Sandwich and Pegwell Bay nature reserve, located near Ramsgate, is enjoyed for its biodiversity, including a variety of birds, and common seals, and is popular regular visitors and birdwatchers.	Kent Wildlife Trust, 2019; Sandwhich Bay Bird Observatory Trust, 2019	OWF	Negative effect on the aesthetic appeal of the seascape	Firestone and Kempton, 2007; Gee and Burkhard, 2010; Hooper et al., 2017a; Kempton et al., 2005; Mangi, 2013; Thanet Offshore Wind Ltd, 2005
			OWF	Ongoing maintenance of the turbines, and future decommissioning, would provide employment opportunities and economic benefits to the region.	Thanet Offshore Wind Ltd, 2005

The construction of the OWF at Thanet is likely to result in positive and negative effects on the delivery of ecosystem services from the area. Table 12 illustrates the flow of ecosystem services in relation to the OWF. For example, it is expected that Thanet OWF would displace some local fishing activity, which would reduce local food provision (Thanet Offshore Wind Ltd, 2005). Turbine foundations present a hazard to fishing gear; concerns over safety, as well as legal and insurance reasons, have meant that fishers are reluctant to set gear within or near OWFs (Alexander et al., 2013; Hooper et al., 2015; Mackinson et al., 2006). However, it has been suggested that by excluding fishing, OWFs would encourage the recovery of fish stocks and lead to over-spill to the surrounding areas (Busch et al., 2011; Langhamer, 2012; Lengkeek et al., 2013). Fish have been shown to aggregate around hard-structures which provide food due to the reef-effect, the development of species rich sessile epifauna communities (Reubens et al., 2011; Svane and Petersen, 2001). This behaviour has been reported for commercial species around offshore wind turbine foundations (Reubens et al., 2013, 2011). Yet, evidence that offshore wind farms benefit fisheries has been inconclusive. For example, there were no significant changes in reported catches before and after the construction of Kentish Flats and North Hoyle wind farms, although catch per unit effort (CPUE) from survey trawls within the Kentish flats wind farm were higher for all species except sole (Mangi, 2013).

Exclusion of fishing activities from inside the wind farm may also be beneficial to biogenic reef systems. Demersal fishing has been shown to damage tubes and remove parts of reefs (Gibb et al., 2014) and are a likely cause of reef destruction (Collins, 2003; Reise and Schubert, 1987). Pre-installation surveys showed extensive trawl damage within the TDS, which included damage to *S. spinulosa* structures (Marine Ecological Surveys Ltd, 2008). There was an increase in *S. spinulosa* reefs reported following the installation of the OWF (Pearce et al., 2014), which may indicate recovery due to an obstruction to trawling. Moreover, OWFs have the potential to enhance crab and lobster fishing. *Cancer pagurus* and *Homarus gammarus* migrate between rocky habitats in search of shelter and food (Krone and Schröder, 2011). It is likely that artificial hard substrata act as stepping stones within extensive soft bottom areas (Krone et al., 2013a). Thus, although it is not the primary goal, an added benefit of the OWF is the creation of new habitat that may also aid restoration of existing natural habitat.

In addition to producing low carbon energy, OWFs are likely to influence levels of atmospheric carbon. It is anticipated that increased biomass, due to colonisation of the turbine foundations, would result in an increased carbon sequestration (Alonso et al., 2012; Burrows et al., 2014; Hooper et al., 2017a; Lange et al., 2010). Further, faecal and other organic matter deposited on the seabed by epifaunal communities would be relocated by deposit feeding and bioturbation activities. As such, OWFs may further enrich sediments and influence primary productivity. Higher levels of chlorophyll-a concentrations have been recorded in sandy sediments around gravity based turbines (Coates et al., 2011). Increased productivity and nutrient cycling are likely to support commercially important species as well as those species seen to be more charismatic and iconic, such as birds and mammals.

Thanet wind farm may have a negative effect on the cultural enjoyment of the area, as it is visible from the eastern coastline of the isle of Thanet peninsula. Public concerns about impact to the aesthetic appeal of coastlines following the construction of OWFs have been widely reported (Firestone and Kempton, 2007; Gee and Burkhard, 2010; Hooper et al., 2017a; Kempton et al., 2005; Mangi, 2013; Thanet Offshore Wind Ltd, 2005). As such, for many residents and visitors to the area, Thanet could have a negative effect on the aesthetic appeal of the seascape. However, the presence of the OWF, as well as a number of others in the region, are expected to support the local economy as ongoing maintenance of the turbines, and future decommissioning, would provide employment opportunities (Thanet Offshore Wind Ltd, 2005).

Several ecosystem services relate to structural elements of the OWF, such as the effect of the turbines on cultural enjoyment of the seascape and the exclusion of fishing. It should be noted that services relating to ecosystem functioning, for example changes in nutrient fluxes or waste treatment, may not be remarkably different to preconstruction levels at the scale of the turbines. Chapter 4 demonstrated that, despite differences in community structure, functional diversity was generally similar between soft sediments, rock reefs and artificial platforms.

5.4.3 Risks to natural capital

Human activities present a number of risks to natural capital and ecosystem services. An asset risk register can be compiled to highlight benefits from natural capital that are at risk (Mace et al., 2015). It is important when compiling the risk register to consider current and future risks to natural capital (Natural Capital Committee, 2017a).

Table 13 shows the risks to natural capital at Thanet OWF and indicates their level of risk to the delivery of ecosystem services. For example, fishing activity presents high risks to the benthic ecosystems. As outlined in section 5.4.2, fishing vessels were active in the region prior to the installation of Thanet OWF (Marine Ecological Surveys Ltd, 2008; Thanet Offshore Wind Ltd, 2005). Whilst gill nets, either anchored or set to drift with the tide, were the main form of fishing gear used by local vessels, trawlers from Belgium and Holland were also active in the area (Marine Ecological Surveys Ltd, 2008; Thanet Offshore Wind Ltd, 2005).

Gill nets have garnered controversy globally as they have been responsible for mass mortality of non-target species in the pelagic zone including sharks, turtles, seabirds and marine mammals (Lewison et al., 2004; Tasker et al., 2000; Uhlmann et al., 2005; Wright and Doulman, 1991). Yet gill nets remain static whilst anchored or are not in contact with the sea bed when set to drift. As such these methods are unlikely to cause major damage to natural capital in benthic systems. On the other hand, trawls are often towed in direct physical contact with the seabed, and can be destructive to benthic habitats (Kaiser et al., 2006; Watling and Norse, 1998). Trawling causes physical damage to the seabed and mortality in non-target species, reduces biomass of benthic fauna, removes biogenic structures and resuspends contaminated sediments (Auster et al., 1996; Bergman and Hup, 1992; Hutchings et al., 1990; Kaiser et al., 2006; Watling and Norse, 1998). Further intensive trawling has been shown to reduce species richness (Collie et al., 1997; Hiddink et al., 2006; Thrush et al., 1998; van Denderen et al., 2014) and alter functional composition of the benthos due to the reduced abundance of suspension feeding species (De Juan et al., 2007; Tillin et al., 2006). As discussed, prior to the installation of Thanet OWF there was extensive trawl damage in the benthos and to *S. spinulosa* structures (Marine Ecological Surveys Ltd, 2008). Hence risks to natural capital and impacts to ecosystem services from fishing prior to the installation of Thanet OWF were considered high (table 13). As OWFs obstruct fishing activities it is expected that Thanet OWF would reduce fishing pressures in the area. This idea is supported by the increase in *S. spinulosa* reefs reported following the installation of Thanet OWF (Pearce et al., 2014). Therefore, fishing was identified as a low risk following the OWF installation (table 13). Exclusion of fishing was identified as a benefit to the environment as it may support the recovery of fish stocks and biogenic habitat (table 12).

Also shown in the risk register (table 13), pollution was determined to represent a high risk to ecosystem services before and after the installation of the OWF. Persistent, bio-accumulating and toxic pollutants are ubiquitous in the marine environment (Klamer et al., 2005), and are introduced through multiple sources, including storm water, sewage sludge, industrial dumping and dredging spoils, and riverine and atmospheric inputs (Ashekuzzaman et al., 2016; Browne et al., 2011; Clark, 2002; Lebreton et al., 2017; Napper and Thompson, 2016; Witte et al., 2016).

Table 13 Comparative risk register showing pre- and post-OWF risks to natural capital and ecosystem services. Risks that are absent prior to the installation of the OWF were registered not-applicable (NA)

Risk	Pre OWF-installation				Post OWF-installation				Confidence
	Provision	Regulating	Supporting	Cultural	Provision	Regulating	Supporting	Cultural	
Climate change	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	High
Decommissioning	▨	▨	▨	▨	🟨	🟥	🟥	🟩	Low
EMF	▨	▨	▨	▨	🟨	🟨	🟨	🟨	Low
Fishing	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	High
Hydrodynamic flow changes	▨	▨	▨	▨	🟩	🟩	🟩	🟩	Low
Invasive species	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	High
Noise	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	Low
Pollution	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	High
Turbine maintenance	▨	▨	▨	▨	🟥	🟥	🟥	🟥	Low

High risk	🟥
Low risk	🟩
Risk unknown	🟨
NA	▨

Heavy metals (e.g. Cu, Zn, Cd and Pb), polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) have been recorded in North Sea sediments (Chapman, 1992; Everaarts and Fischer, 1992; Witte et al., 2016). The accumulation of heavy metals in marine organisms can cause damage to tissues and DNA, interfere with tissue regeneration, inhibit growth, reduce fertility, and cause deformities and mortality (Ashekuzzaman et al., 2016; Kennish, 1996). Metals accumulated in marine organisms can be bioaccumulated and biomagnified in upper trophic species (Ashekuzzaman et al., 2016). For example, bioaccumulation of mercury (Hg) has been demonstrated in marine mammals and has been linked to neurotoxicity and immunotoxicity (Basu et al., 2009; Frouin et al., 2012; Jeffries et al., 2016; Krey et al., 2015). Due to bioaccumulation, heavy metal contamination in the marine environment presents a risk to human health (Ashekuzzaman et al., 2016).

More recently, there has been growing awareness of microplastics accumulating in the marine environment and organisms. Lipophilic components of plastics adsorb toxic chemicals from surrounding marine water (Sharma and Chatterjee, 2017), such as PCBs, PAHs and dichlorodiphenyltrichloroethane (DDT) (Van Cauwenberghe et al., 2015). Their small size make microplastics bioavailable to marine organisms (Cole et al., 2011). There is a growing list of species in which plastics, or plastic-derived chemicals, have been reported, including zooplankton (Cole et al., 2013; Desforges et al., 2015; Frias et al., 2014; Thompson et al., 2019), bivalves (Van Cauwenberghe and Janssen, 2014), echinoderms (Graham and Thompson, 2009), decapods (Devriese et al., 2015), fish (Foekema et al., 2013), and seabirds (Tanaka, 2017). Although the effects of chronic microplastic exposure and accumulation are unclear (Carbery et al., 2018; Van Cauwenberghe et al., 2013) the possible negative effects to human health from consuming microplastic contaminated seafood is of great concern (Carbery et al., 2018; Sharma and Chatterjee, 2017).

Climate change was also identified as a high risk to all ecosystem service categories in the risk register (table 13). Increasing levels of atmospheric CO_2 have led to higher sea surface temperatures (SSTs), sea levels, storm frequency and wind velocity, and resulted in changes in ocean circulation, and nutrient loads (Harley et al., 2006). In addition, higher levels of atmospheric CO_2 raise the level of dissolved CO_2 in sea water, which forms carbonic acid (H_2CO_3) and reduces pH (Brierley and Kingsford, 2009; Harley et al., 2006; IPCC, 2014, 2007; Rahmstorf, 2007). There is considerable evidence that changes to oceanographic conditions due to rising CO_2 levels effect the survival and performance of marine organisms (Birchenough et al., 2015; Harley et al., 2006; Kirby et al., 2007; Neumann et al., 2016; Shirayama and Thornton, 2005; Vaquer-Sunyer and Duarte, 2011). Further, changes in seawater chemistry due to ocean acidification can affect solubility, speciation and distribution of metals in water and sediments, as well as the metal toxicity to marine organisms (Ivanina and Sokolova, 2015).

The installation of an OWF would modify marine habitats and present a new set of risks and opportunities for natural capital. For example, the substructures would alter the local hydrodynamic regime (Degraer et al., 2009; Matutano et al., 2016; Miller et al., 2013). It has been suggested that turbulences resulting from local changes in hydrodynamic regimes could cause resuspension of fine sediments which could reduce light penetration and smother existing benthic communities (Hiscock et al., 2002). At Thanet OWF, plumes of suspended particulate matter >10km have been reported downstream of turbines (Vanhellemont and Ruddick, 2014). Although, Baeye and Fettweis (2015) concluded that rather than scouring at the seabed, epibenthic communities on the structure and scour protection at Belwind OWF were the main source of suspended particulate matter in plumes. Nevertheless, changes in hydrodynamic flow are likely to have a negative impact on ecosystem services at the local scale. Although it is uncertain if this effect would scale up across the OWF.

During operation, OWFs would introduce mechanical noise from gears, generators, hydraulic systems and rotor blades (Lindeboom et al., 2011) as well as electromagnetic fields (EMF) (Gill et al., 2005, 2012; Gill, 2005). Turbines in Thanet OWF are interconnected by a buried 33 kV cable network (Thanet Offshore Wind Ltd, 2005). This current is stepped up to 132 kV at an offshore substation before reaching the onshore substation via the export cable and joining the national grid (Thanet Offshore Wind Ltd, 2005). Submarine cables can generate an EMF similar to that of the Earth's magnetic field (Walker, 2001). Thus, cables have the potential to attract or repel EM-sensitive species, which are thought to be sensitive to the Earth's magnetic field (e.g. migratory fish, elasmobranchs, mammals, chelonians and crustaceans) (Gill et al., 2012; Wiltschko and Wiltschko, 1995).

Noise levels from OWFs in production are lower than those emitted by pile driving during construction, however, operational turbines provide potentially long-term chronic exposure (Hawkins et al., 2014). Although, sound levels from OWFs have not been found to be significantly higher than background noise levels (Nedwell et al., 2007). Nonetheless, most noise emitted by operational offshore wind turbines is low frequency (<1000 Hz) (Andersson et al., 2011; Hawkins et al., 2014) and are detectable by sound sensitive fish over several kilometres (Andersson et al., 2011).

The effects of chronic exposure to turbine noise and EMF are unclear. However, despite exposure to noise and EMF, turbine substructures support complex and diverse communities (Bouma, 2012; Coates et al., 2011; Degraer et al., 2012; Kerckhof et al., 2012). Further, there is evidence that ecosystem functioning in communities on artificial structures is comparable with those from natural habitat (chapter 4). Thus, the risks to ecosystem services from turbine noise and EMF were identified as low in the risk register (table 13).

It has been highlighted that OWF have the potential to facilitate the spread on non-native species (Adams et al., 2014; De Mesel et al., 2015; Wilhelmsson and Malm, 2008). Artificial substrata, including OWFs, have been shown to be readily colonised by opportunistic non-native species (De Mesel et al., 2015; Gill, 2005; Gittenberger et al., 2009; Glasby et al., 2007; Kerckhof et al., 2011; Lindeboom et al., 2011; Page et al., 2006). For example, Kerckhof et al (2011) found numerous non-native species, including *Elminus modestus*, *Crassostrea gigas*, *M. coccopoma*, *Telmatogeton japonicus*, *Jassa marmorata* and *B. perforatus*, colonised foundations in C-Power and Belwind OWFs in the Southern North Sea. They noted, however, that these species were already known to occur in the southern North Sea.

The risk to natural capital from non-native species prior to the OWF installation was considered high in the risk register (table 13). The North Sea has been subject to intense invasion by non-native species (Paavola et al., 2005). Since before the installation of offshore wind turbines, non-native species have been transported via vessel traffic, either as adults attached to the hull or larvae in ballast tanks, and the aquaculture trade (Reise et al., 1999). For instance, up to 32 species have been reported to have been introduced with American and Pacific oysters (*C. virginica* and *C. gigas*) (Reise et al., 1999).

Non-native species present an ecological and economic risk (Collingridge et al., 2014; Gallardo et al., 2013). For example, collapses of fish stocks in the Black Sea and Caspian Sea were attributed to predation on fish eggs and larvae, and competition with zooplanktivorous fish by the invasive ctenophore *Mnemiopsis leidyi* (Shiganova et al., 2003). This species was first reported in the North Sea in 2005 (Oliveira, 2007) but is now widespread (Javidpour et al., 2009). Another species reported in the North Sea, having previously been blamed for causing ecological disaster in the Black Sea is the gastropod *Rapana venosa* (Nieweg et al., 2005). This species is a voracious predator, mainly of bivalves, and presents a risk to fisheries and aquaculture of commercial bivalves, such as mussels (*M. edulis*), pacific oysters (*C. gigas*) and cockles (*Cerastoderma edule*) (Nieweg et al., 2005). The installation of Thanet OWF does not reduce the risk from invasive species. Rather, by providing an intertidal zone in the offshore environment Thanet OWF may provide a foothold for intertidal invasive species. Indeed, Kerckhof et al (2010) found that the greatest number of non-native species were in the intertidal zone. As such, it was determined that the risk to natural capital from non-native species after the installation of Thanet OWF remained high. This notwithstanding, findings from chapter 3 indicate community structure between soft sediments and turbine foundations would differ, evidence from chapter 4 suggests that ecosystem functioning would not be significantly different between habitats. As ecosystem functioning is integral to the provision of ecosystem services, the results from chapter 4 suggest that a change in community structure would present a low risk to the delivery of ecosystem services. Although, it is not understood if this would be true of non-native species that may out compete and over-predate indigenous fauna and flora or introduce disease.

Risks from maintenance activities were also considered as part of this assessment. Maintenance of the structure above the waterline, which includes inspection, replacement of fluids and servicing of mechanical parts, is typically carried out at 6 month intervals (Chan and Mo, 2017). Below the waterline, maintenance can include inspection and cleaning of the foundation (Buck and Langan, 2017). Inspection of foundations is recommended after a period of 5-10 years (Buck and Langan, 2017). As such, cleaning is likely to be an irregular activity. Although organisms removed from the structure during cleaning would be deposited on the seabed, the biomass removed by cleaning over the life of the OWF would be low compared with typical levels deposition from epibenthic communities.

Nonetheless, carrying out maintenance would result in increased vessel traffic, introducing additional noise to the environment. Further, as vessels manoeuvre close to the turbines there is a risk of collision with the structure (Presencia and Shafiee, 2018). A ship-turbine collision could damage or destroy the foundation and could cause oil or chemical spills from the vessel (Presencia and Shafiee, 2018). It has been noted that few ship-turbine collisions have been recorded, although this may be due to accidents going unreported (Presencia and Shafiee, 2018). As the offshore wind energy industry expands there would be an increase in the number of maintenance vessels close to turbines, increasing the risk of collisions. Due to the severity of the consequences from collisions the risk to ecosystem services from maintenance activities was considered high. However, confidence in this assessment was considered to be low as the reported frequency of ship-turbine collisions was low and it is uncertain as to whether incidents are going unreported.

Impacts associated with construction of OWFs have received extensive coverage in the literature (Bailey et al., 2014; Inger et al., 2009; Mueller-blenkle et al., 2010; Perrow et al., 2011; Wilson et al., 2010). Yet the decommissioning process, which would also cause considerable disturbance to offshore ecosystems, has received little consideration (Fowler et al., 2018). In line with current policies wind turbines and their substructures are expected to be removed at the end of their operational life. Complete removal of wind turbine substructures and cables would temporarily cause destruction of the seabed and benthic communities, resuspending contaminated sediments, spreading non-native species and reducing biological connectivity (ETSU, 2000; Fowler et al., 2018, 2014; Macreadie et al., 2011). Large plumes of suspended sediments may obstruct fish from feeding, and smother benthic communities and newly settled larvae (ETSU, 2000; Januario et al., 2007). Along with damage caused by the physical removal of the foundations, equipment used, such as jack-up vessels, anchors and remote ploughs, would disturb the sediment and cause localised removal of benthic communities (Januario et al., 2007). In addition, the disposal of materials, such as turbine oil and coolants, onshore may pose a risk to human health if soils and groundwater become contaminated (Januario et al., 2007).

Removing the structures would also remove the benefits associated with epibenthic communities. The level of risk decommissioning would present to regulating and supporting ecosystem services were considered to be high. In developing the risk register (table 13), with the exception of the loss of colonising communities, most impacts are likely to be high, but temporary. Conversely, the risk to cultural services was thought to be low and the risk to provisioning services is unknown. Complete decommissioning would restore the sea scape and reopen areas for fishing. This would certainly improve the cultural experience of those who feel OWFs negatively affect the seascape. Moreover, it would allow displaced fishing activities to continue. But it is not clear what level of impact decommissioning would have on populations of commercial fish.

As discussed in section 5.5.3 below, decisions made at the end of the OWF operational life may mitigate risks. However, without considerable revision to current policies such alternatives are unlikely to become common practice.

5.5 Identifying and weighing up options

As part of the assessment of natural capital, one must consider options to maximise natural capital and ecosystem services. This natural capital approach to assess changes since the installation of Thanet OWF is particularly relevant and timely given plans to extend Thanet OWF by up to 34 turbines (Royal Haskoning, 2016).

5.5.1 Habitat creation

A by-product of constructing an OWF is the creation of habitat by introducing hard substrate that penetrates the water column and introduces an intertidal zone. Some developers have taken the opportunity to create additional habitat separate to what is necessary for the turbines and cables. Recently Orsted used large stones of various sizes to create 25 artificial reefs at Anholt OWF in Denmark (Orsted, 2019). Were this performed at Thanet, rock reefs would further increase habitat heterogeneity, creating shelter and opportunities for feeding for mobile demersal megafauna. It is expected that cavities would attract lobsters, crabs and Gadidae spp. (Orsted, 2019). Such an option could encourage new fisheries activities to replace those that were displaced by the installation of the OWF. It was recently reported that lobster and edible crabs were being targeted in the vicinity of Thanet OWF (Vattenfall Wind Power Ltd, 2017b). Thus, added rocky habitat, in which lobsters and crabs thrive (Christie et al., 2014) may support these commercially important taxa. It has been suggested that rock scour protection around turbines could increase the yield of crab and lobsters (Christie et al., 2014). Scour protection was not added around monopiles in Thanet OWF but is being considered for monopiles to be installed in Thanet extension (Vattenfall Wind Power Ltd, 2017a). In order to enhance natural capital, scour protection could also be introduced around the existing turbines in Thanet OWF.

5.5.2 Co-location of fisheries and aquaculture

The possibility of co-location of decapod fisheries within OWFs has received attention in the literature (Hooper et al., 2015; Hooper and Austen, 2014) along with co-location of mussel and oyster aquaculture (Hieronymus et al., 2004; Michler-Cieluch et al., 2009; van den Burg et al., 2017). Designs have been proposed for a collar system, that could be attached to foundations, and a longline system that could be deployed between foundations, to which mussel ropes and oyster cages could be attached (Hieronymus et al., 2004; van den Burg et al., 2017). A recent study trialled a long line system for offshore mussel production in Belwind OWF in the Belgian part of the North Sea (Nevejan, 2018). The study showed promise; the long line systems were robust and there was rapid growth of mussels with good meat content. Co-location may mitigate the societal and economic impact on the fishing industry, and help developers to engage with local fishing communities (Christie et al., 2014).

5.5.3 Decommissioning

Decommissioning options that minimise the loss of natural capital should also be explored. Due to legal, financial, public and environmental concerns plans for decommissioning are generally included in the licensing and consent proposals for OWFs as part of the EIA process (Januario et al., 2007; Smyth et al., 2015). Typically, decommissioning would involve complete removal of all structures. The intention being to return the habitat to preinstallation conditions (Fowler et al., 2018). Yet given human activities have impacted the region prior to installation, returning the site to a pre-installation condition would mean returning it to an impacted site whilst losing the benefits provided by the structures. Also decommissioning would be costly, carry risks and may not fully restore pre-installation conditions, such as hydrodynamic flow (Smyth et al., 2015).

In decommissioning, international legal obligations typically call for full removal of structures from the seabed (Smyth et al., 2015). Decommissioning guidelines were originally developed for the oil and gas industry where-by a structure could not be reused for its intended purpose once an oil or gas field was exhausted (Smyth et al., 2015). Offshore wind turbines differ in that repowering or replacing machines would allow for continued exploitation of wind resources (Smyth et al., 2015) whilst maintaining natural capital and ecosystem services developed over the lifetime of the OWF. Recent updates to guidelines acknowledge this, as well as the associated risks of decommissioning. For instance, under the UK Energy Act 2004 alternatives to complete decommissioning may be considered, amongst other reasons, if the structure can be re-used or serves a new use, such as enhancing living resources, or if removal presents an unacceptable risk to personnel or the environment (Department of Energy and Climate Change, 2011).

An alternative to repowering could be partial decommissioning, an option first applied to oil and gas structures under rigs-to-reefs programs (Cripps and Aabel, 2002; Macreadie et al., 2011). Partial decommissioning of an OWF, dubbed renewables-to-reefs (Fowler et al., 2015; Smyth et al., 2015), involves removal of the structural elements above the waterline. Under this option the foundations could be toppled *in situ* or cut close to the sea bed, so as not to present a hazard to navigation (Fowler et al., 2018; Smyth et al., 2015). Unlike repowering, partial removal would not allow for continued energy generation. Further, as zonation occurs in respect to depth on offshore structures (De Mesel et al., 2015; Forteath et al., 1982; Guerin et al., 2007; Kerckhof et al., 2009; Mallat et al., 2014; Wolfson et al., 1979) partial decommissioning would also partially remove natural capital. As such, a partially decommissioned OWF may differ from an active OWF in the delivery of ecosystem services.

5.5.4 Assessment of options

The options considered in the decision-making process are likely to vary depending on the goals of the developers in conjunction with other stakeholders and environmental protection. For example, given Thanet OWF is expected to displace local fishing activities, building rock reefs between turbine foundations and/or installing aquaculture systems may be a preferred option to. The use of highly destructive, mobile fishing would be excluded whilst alternative fisheries, that don’t utilise mobile gear, would be encouraged. Although, it would be important to avoid locations of biogenic reefs, which are protected habitats. Alternatively, were the goal to conserve and allow recovery of existing natural capital, such as *Sabellaria* reefs and mussel beds, simply excluding fishing from within the extent of the OWF without developing new reefs could be sufficient.

Repowering turbines at the end of their operational life might be preferential to partial decommissioning. In addition to preventing further disturbance to the site, repowering Thanet OWF could prevent disturbance to an alternative site as it may negate the need for another OWF to be installed. Moreover, as the installation phase is the most energy intensive part of the OWFs life-cycle (Kaldellis and Apostolou, 2017) repowering the turbines, and thus extending their operational life, would further reduce the carbon footprint of the OWF.

The legal framework for decommissioning offshore renewable energy installations and associated cables is laid-out in the UK Energy Act 2004 (chapter 2, section 95) (Januario et al., 2007). Partial decommissioning could be considered preferential to complete removal of the structure and scour protection as it preserves some habitat. Yet, it is stipulated under the UK Energy Act 2004 that formation of an artificial reef would be unacceptable grounds to propose leaving a structure in place (Department of Energy and Climate Change, 2011). Thus, for Thanet OWF, partial decommissioning, without providing a further use, may be unfeasible under the current policy. However, given evidence that structures support natural capital and ecosystem services, there is scope for this policy to be revisited. Particularly given the UK governments stance on protecting and enhancing natural capital. Based on this assessment, although Thanet OWF would present a number of risks to the environment and aspects of the economy, it would provide greater benefit to both. For instance, the installation of an OWF would introduce multiple species and raise biomass within the development area (table 11). As shown in table 12, increased local biomass would raise carbon sequestration and remediate waste and toxins, as well as provide feeding opportunities for commercially exploited species.

The trade-offs support the need to consider revisiting current policies where it is determined that structures provide greater benefits than risks through promoting natural capital and ecosystem services. Were such provisions made in policy there would also be a need for continued monitoring of natural capital to assess the risks and benefits on a project by project basis.

5.6 **Discussion**

The natural capital approach has gained momentum in recent years as a result of a greater appreciation of the role of natural assets and biodiversity in supporting human health, wellbeing and economic prosperity. There has been a growing number of projects concerned with assessing natural capital and ecosystem services in terrestrial systems (Lovett et al., 2018; Natural England, 2012; RSPB, 2017). Whereas, few studies have addressed natural capital in marine systems (Medcalf et al., 2012; Picone et al., 2017). Therefore, links between natural capital assets and ecosystem services are better defined in terrestrial and freshwater systems than marine (Mace et al., 2015).

Current commitments to enhance the natural environment have been developed around the natural capital approach (HM Government, 2018). In 2015 the UK natural capital committee outlined a methodology for assessing natural capital in its third annual state of natural capital report (Natural Capital Committee, 2015). Building upon this methodology, in 2017 the natural capital committee released its guidance for assessing natural capital to make decisions about the natural environment (Natural Capital Committee, 2017a). In this study the natural capital committee’s methodology was applied to assess the effect of Thanet OWF on natural capital and the delivery of ecosystem services in a coastal region of the southern North Sea, an area of high activity for the offshore wind industry.

5.6.1 Changes in natural capital and ecosystem services

This case study has demonstrated the potential for a natural capital assessment to provide a more complete and integrated approach to assessing changes in marine ecosystems due to offshore development. The current EIA framework provides an indication of likely impacts to the environment from the installation of the OWF for local planning authorities (UK Government, 2017). Yet, EIAs can emphasise negative impacts and fail to adequately capture positive effects (Hooper et al., 2017b; Smart et al., 2014), and take a siloed approach to issues. Herein lies the strength of the natural capital approach, which is intended to capture changes in natural capital within a system, take an integrated approach and evaluate the flow of benefits and risks. Thus, trade-offs are brought in to focus and can be considered in the decision-making process.

Comparison of natural assets between the TDS, pre-OWF installation, and energy platforms in the southern North Sea suggested that natural capital would increase following the installation of the Thanet OWF. Prior to construction of the OWF the development site was characterised by sand and sandy gravel, with varying proportions of silt and clay (Pearce et al., 2014; figure 33). The site had relatively low heterogeneity, although there were large sand waves produced by the local current regime (Gardline Geosurvey Ltd., 2012, 2007) and biogenic reefs covered some of the area. *S. spinulosa* reefs and a small mussel bed had been identified in the Thanet development site prior to the construction of the OWF (Pearce et al., 2014). Further, reef building polychaetes *S. spinulosa* and *L. conchilega,* and mussels (Mytilidae), were identified in samples within or close to the TDS (figure 34). However, there was evidence of damage to the *S. spinulosa* reefs from fishing trawlers (Marine Ecological Surveys Ltd, 2008).

In contrast, the installation of the wind turbines introduced habitat heterogeneity, as well as an intertidal region, providing habitat for hard substrate and intertidal communities. In addition, there was an increase in *S. spinulosa* reefs following the installation of Thanet OWF (Pearce et al., 2014), which may be a result of reduced disturbance from trawling.

As described, community data from offshore energy platforms were used as a proxy for communities on the wind turbine substructures (figure 31). The offshore energy platforms were shown to have a greater number of species and mean abundance than recorded within sediments at the Thanet development area (table 11). This is supported by the finding of chapter 3 that showed differences in community composition between the Thanet development site and the offshore energy platforms were significant. Thus, the installation of the turbines is likely to increase local species richness and biomass.

Based on the asset register (section 5.4.1) ecosystem services before and after the installation of Thanet OWF were evaluated, demonstrating the trade-offs in goods and benefits. For example, the TDS and surrounding area was used by local, national and European fishing vessels prior to the installation of the OWF (Marine Ecological Surveys Ltd, 2008; Thanet Offshore Wind Ltd, 2005). By creating an obstruction to trawling and drift net fishing the OWF would cause a reduction in food provision. Yet, the OWF may therefore function as a no-take zone, which could support local fish stocks, and allow recovery of the seabed and biogenic reef structures (Lindeboom et al., 2011). Thus, in the long term, the OWF may further support provision of food along with other ecosystem services. Additionally, as presented in sections 5.1 and 5.2 the OWF could present opportunities for alternative fisheries and aquaculture, further increasing food provision.

In business, risk registers are a useful tool for identifying high risk operations that require attention (Mace et al., 2015). In terms of a natural capital assessment, a risk register is intended to highlight risks to natural capital and ecosystem services. An advantage of risk registers is that they can be compiled in absence of full knowledge of a system (Mace et al., 2015).

Risks were identified as low, high or unknown (table 13) and a corresponding level of confidence, whether low or high, was given. Where risks were absent prior to the installation of the OWF risks were classified as not applicable (NA). To illustrate, it was determined that before the installation of Thanet OWF fishing presented a high risk to provisioning, regulating and supporting ecosystem services. This was by and large due to the destructive nature of trawling. Following the installation of Thanet OWF, which was expected to obstruct trawling, the level of risk was reduced to low as less destructive alternatives could be encouraged, such as lobster fisheries and mussel or oyster aquaculture. In addition, other fisheries in the region may be supported by overspill from the OWF. As the relationship between OWFs and fishing has been discussed extensively in the literature the author could be confident in the classification of this risk. Thus, confidence was high. Conversely, the effect of noise produced by offshore wind turbines on benthic organisms and ecosystems remains unclear. For this reason, the risks from noise were classified as unknown and the confidence was low.

Despite the importance of marine ecosystems in providing services, data on the extent of marine habitats and pressures exerted on them are not comprehensive (Medcalf et al., 2012). Gaps in the data relating to natural capital became apparent whilst compiling the asset register and asset risk register. This paucity in data was a limiting factor; knowledge of the extent and condition of natural assets is important for developing an asset register and asset risk register (Mace et al., 2015; Natural Capital Committee, 2017a). Available data for the TDS were collected in the course of an EIA and included samples collected from discrete and irregular locations within or close to the TDS. Further, benthic samples were relatively small (10 cm^2), meaning only a small area of the seabed (<10 m^2) was surveyed. Where remote sensing was used to conduct fine scale surveys only *S. spinulosa* reefs were mapped (Pearce et al., 2014). As such, gauging the condition and extent of natural assets, in practice, proved unfeasible. At a coarse scale, it was estimated that sand and sandy gravel substrate covered up to 93% of the TDS. The installation of the turbines would reduce this coverage by a small margin (<0.05%), although they would provide an area of hard substrate habitat 20 times larger than the soft substrate lost. However, it was acknowledged that the extent of soft substrate was likely to be an overestimate as the full extent of mussel beds and *L. conchilega* structures (if present) were unknown. Distributions of species inhabiting the sediments could not be accurately determined. Further, data on the distribution of species inhabiting sediments after the installation of Thanet OWF were not available. It should not be assumed that habitat between turbines would be unaltered by the turbine substructures. For instance, mussel shell falls from turbine foundations and aggregates on the sea floor, this can modify sediment grain size (Coates et al., 2011, 2014; Krone et al., 2013b). Moreover, faeces and pseudofaeces from mussels can enrich sediments, further supporting infaunal communities (Coates et al., 2011, 2014; Köller et al., 2006; Maar et al., 2009).

In addition, wind turbine substructures would alter the hydrodynamic regime (Degraer et al., 2009; Matutano et al., 2016; Miller et al., 2013), resuspending fine sediments which can reduce light penetration and smother existing benthic communities (Hiscock et al., 2002). It is likely that these changes would vary throughout the wind farm based on the direction and speed of currents and tides and the position of turbines in the OWF. More specifically, the hydrodynamic regime experienced by communities on or near turbines on the leading edge of the OWF would differ from those experienced around turbines in the centre or the far edge of the OWF. Such changes were not known and could not be estimated or assumed as part of the natural capital assessment.

As such, trends in their extent, from before and after the OWF installation, could not be determined. Similar limitations were identified in a study by Medcalf et al. (2012) when mapping natural capital at Dogger Bank in the North Sea. Whilst further surveys would assist in filling these gaps, due to the methods and technology required collecting data would be very expensive (Medcalf et al., 2012). Some data gaps could be filled using remote sensing Techniques. Sidescan sonar was shown to be effective in mapping the distribution of *S. spinulosa* reefs in areas of the TDS (Pearce et al., 2014). It has also been used to measure seagrass cover (Greene et al., 2018), and to classify seabed topography and substrate (Buscombe, 2017; Fakiris et al., 2015).

In terrestrial and freshwater systems proxies, habitats with similar biophysical components and processes, have been used to fill knowledge gaps (Mace et al., 2015). However, there is a lack of suitable proxies for marine ecosystems due to a lack of available data and agreed methods to derive proxies (Medcalf et al., 2012). Nonetheless, it has been argued that the importance of ecosystem concepts compels exploration of the spatial extent of ecosystem services despite knowledge gaps (Medcalf et al., 2012).

In this case study, ecosystem services were linked to natural capital based on published literature to illustrate potential changes following the installation of Thanet OWF. However, the focus of this assessment was at the scale of the turbine. Further study is needed to incorporate changes in natural capital associated with sediments between turbines to better understand the flow of ecosystem services within an OWF.

5.6.2 Application of the natural capital approach to an offshore wind farm

A natural capital assessment can be utilised to assess trends in natural capital over the life of the OWF, incorporating trade-offs between benefits and risks. It could be a valuable tool; demonstrating where practices are unsustainable given the condition of natural capital. It could thus inform management decisions which enhance natural capital and mitigate risks. Natural capital assessments may also inform decisions about decommissioning turbines at the end of their operational life and future use of the site.

Based on the outcomes of this case study it would be advantageous to the sustainability of ecosystem services if developers were to invest in natural capital. In the case of Thanet OWF and the Thanet extension this could mean installing scour protection around the turbines or building a number of reefs within the OWF. Installing rocky habitat over a relatively small area within the TDS could assist establishment of new fisheries that do not utilise mobile fishing gear, such as lobster fisheries (Christie et al., 2014). Commercial lobster fisheries typically use baited traps called pots which sit stationary on the seabed (Bannister and Addison, 1998; Schmalenbach et al., 2011; Treble et al., 1998). This would provide a potential alternative fishery and associated income which could contribute to economic prosperity in the area if the displaced fisheries could be replaced by a more lucrative fishery. Alternative fishery outcomes are evidently a topic that requires further exploration.

Co-use of Thanet OWF and the Thanet extension for aquaculture is another option that has potential and would contribute to the local economy and increase food provision (Busch et al., 2011). Before co-use can be established however, consideration must be given to the end-of-life for the OWF. Aquaculture systems could be attached to turbine foundations (Hieronymus et al., 2004). If the foundations are to be removed, some aquaculture systems may also need to be removed.

Offshore wind turbines are a commercial asset that provide the major advantage of low carbon energy (Kaldellis and Apostolou, 2017). Yet, they may also be viewed as a novel artificial habitat. The turbine foundations, and the epibenthic communities they support, provide shelter and opportunities for feeding for mobile demersal and pelagic species (Gill, 2005; Krone et al., 2013b; Langhamer, 2012; Wilhelmsson and Malm, 2008; Wilson and Elliott, 2009; Wilson et al., 2010). Given that a project may improve natural capital over the operational lifespan by providing manmade, but productive, habitat, there is a case to be made for revising current legislation regarding decommissioning of offshore wind turbines. At present, decommissioning aims to return the habitat to preinstallation conditions (Fowler et al., 2018). For much of the southern North Sea, including the TDS, this would mean returning the site to one that is dominated by sandy and sandy gravel seabed, with little hard substrate. Whilst well intentioned, this goal may be arbitrary and ultimately counterproductive. There is need for a shift from the conservation perspective to one that recognises ecosystem services and acknowledges that the pre-development seabed may already be highly impacted from human activities.

There is evidence that hard substrate was once common in the southern North Sea. Historical maps show 20-35% of the Dutch continental shelf was once covered by hard substrate, such as oyster beds and coarse peat banks (Lengkeek et al., 2013; Olsen, 1883; Whitehead and Goodchild, 1909). Oyster beds were largely lost due to overexploitation (Franke and Gutow, 2004; Reise, 1982). It is also understood that *Sabellaria* reefs were once more extensive in the North Sea and were lost due to fishing activities (de Groot, 1984; Reise, 1982).

5.6.3 Obtaining data for monitoring natural capital

Management of natural capital requires continued monitoring of the extent, quality and quantity of natural assets. There has been criticism that environmental monitoring programmes, a requirement for marine developments under EIAs and numerous international directives, lack the necessary information at relevant ecosystem scales to discern the effects of renewable energy installations on benthic ecosystems (Wilding et al., 2017). To effectively assess trends in natural capital over the life time of the OWF a monitoring programme that covers a greater proportion of the OWF extent is required. However, consideration must be given to ecologically meaningful spatial and temporal scales (Wilding et al., 2017). For example, in this case study natural capital change following the installation of Thanet OWF was considered mainly at the scale of the turbine, based on available data from energy platforms. This was due to unavailability of data from soft sediment habitats following the installation of the OWF. Future monitoring should include between turbine habitats as well as the turbine foundations. Further, to effectively make comparisons over temporal scales, repeated sampling should be carried out from the same locations year on year, which has been recognised in reef systems (Brown et al., 2004; Johnson et al., 2012). Locations sampled during benthic surveys in 2005 and 2007 as part of the EIA for Thanet OWF differed (Marine Ecological Surveys Ltd, 2008). Therefore, direct comparisons could not be made between samples from 2005 and 2007.

Temporary sampling structures, which provide hard surfaces for colonisation and can be rapidly deployed and recovered from a small vessel, could also be used to aid long term monitoring. The details and designs for a potential temporary sampling structure and mooring system have been presented in chapter 1 (section 1.3.1). If deployed prior to the installation of the OWF, the structures could indicate how natural capital would change following the installation of an OWF compared with the pre-installation habitat. Temporary structures would provide a snapshot of potential communities, including invasive species, that would colonise offshore energy structures. As an additional benefit, they would provide fixed locations for repeated sampling from the structure and nearby seabed. Thus, samples from temporary structures could indicate changes in quality, quantity and extent of natural capital. Based on this evidence, changes in ecosystem services once an OWF has been installed could be more accurately estimated. However, a drawback to temporary structures is that, were the structures or mooring system damaged or moved, possibly due to severe weather or a vessel strike, then long-term data could be lost.

Temporary structures can also be used to build evidence to answer specific ecological and engineering questions. For example, the design presented in chapter 1 was intended to investigate the influence of surface orientation on epibenthic colonisation. This is particularly relevant given the trend for larger turbines to be installed at greater depths (Doherty, 2011); jacket foundations, which consist of structural members at multiple orientations, have been used to support wind turbines in depths of 35 to 60 metres (Doherty, 2011). Different materials and coatings, which may vary in surface roughness as well as chemical composition, could also be included in the array of sampling structures. By understanding patterns in zonation and succession relevant to surface orientation, as well as depth and surface roughness, due to materials or anti-corrosion coatings, we may better predict the effects of novel structures on community dynamics.

Moreover, colonisation by marine organisms has been shown to increase cross sectional areas and surface roughness (Fevåg, 2012; Jusoh and Wolfram, 1996; Shi et al., 2012a; Theophanatos and Wolfram, 1989). Therefore, colonisation increases hydrodynamic loading on the structure (Yan and Yan, 2003) and influences fatigue behaviour of jacket structures (Heaf, 1979; Shi et al., 2012a). An increase in fatigue of the structure would mean a decrease in the functional life of the turbine and/or an increase in maintenance. Thus, samples from temporary structures could inform turbine design and maintenance decisions.

Photography is a useful tool that is frequently used in benthic surveys to record and identify epibenthic communities (Bouma, 2012; Marine Ecological Surveys Ltd, 2008; Ponti et al., 2011; Stachowicz et al., 2002). The advent of high definition 3-D photogrammetry provides a potential technique to quantify the spatially heterogenous colonisation of structures with high accuracy and assist the determination of the roughness of surfaces following colonisation.

To assess the potential of photogrammetry to monitor benthic colonisation of subsurface structures a test using photogrammetry developed at the Scottish Association of Marine Science (SAMS) was performed on existing intertidal structures. Piles from two coastal structures in Suffolk were selected, a coastal defence groyne in Lowestoft and Southwold pier. Digital images and videos were taken at 0.5-1 m from the surface, with an overlap of 70% between images. Photographs were taken with a canon 7d mark II SLR and videos recorded with a GoPro Hero 3 camera. The images were processed externally and rendered in to 3D models. Figure 35 shows the 3D render from the coastal defence groyne in Lowestoft and figure 36 shows the 3D render from the Pile from Southwold pier. The results of the photogrammetry, including appendix G (table G-1 and table G-2) indicate variability in surface roughness even over short distances (several millimetres). The deviation from the object surface was measured at several points increasing in height from the seabed. Figure 35 shows barnacle clusters with deviations from the surface of more than 10 mm (yellow-red region) greater than at areas of mean surface deviation (green regions) 20-30 mm away.

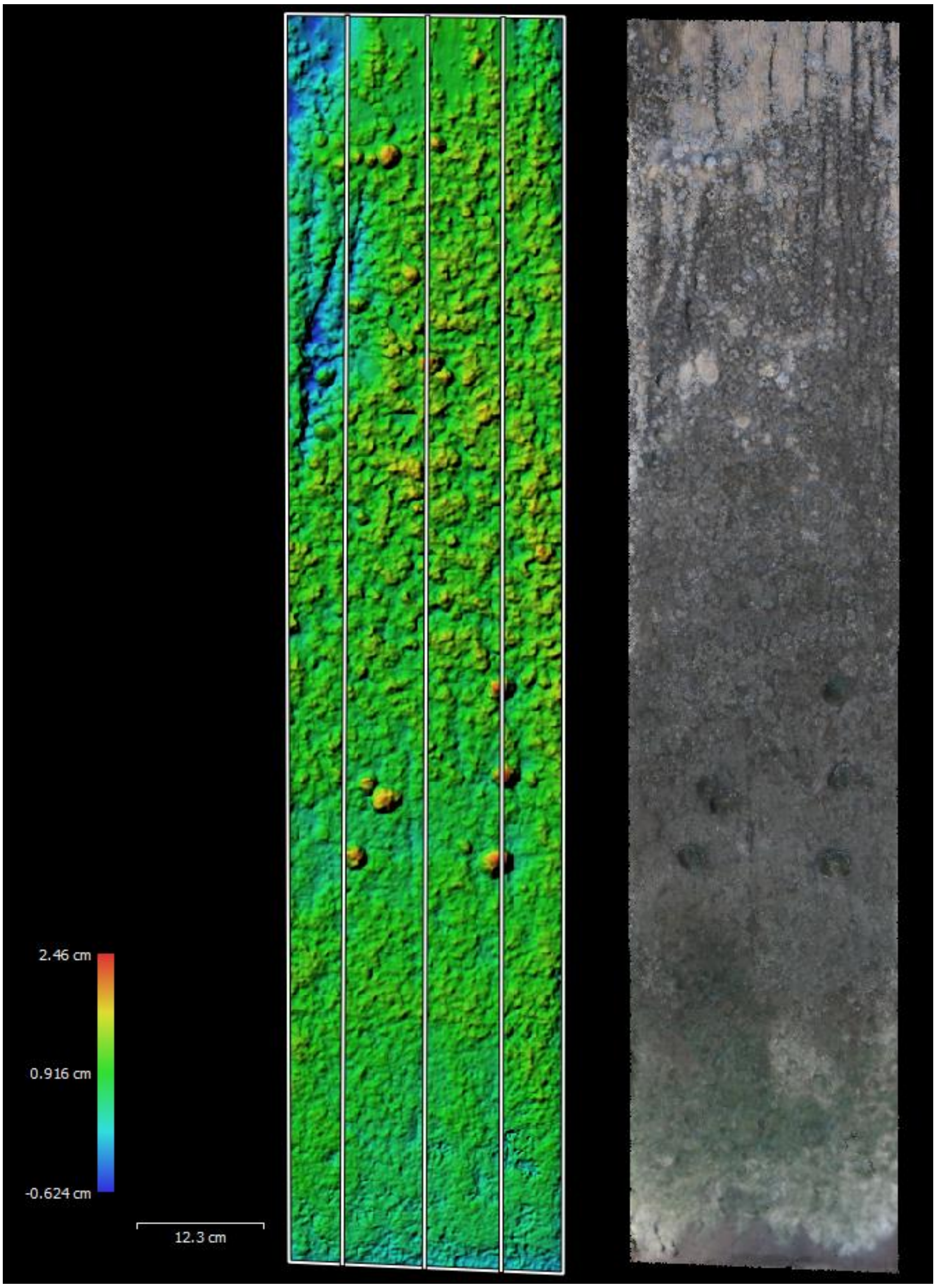

Figure 35 Photogrammetry render showing one side of the coastal defence groyne pile. The image on the left shows the deviation from the mean thickness in cms (red > mean, green ≅ mean and blue < mean as shown by the vertical scale in the left corner). The image on the right shows the original images of the surface merged. The horizontal scale bar in the left had corner indicates size.

In figure 36 the mean deviation is skewed by the curvature of the surface. As such, yellow/orange regions, rather than green, are closer to the mean. Figure 35 shows that the majority of epifauna, and thus the roughest surfaces, occur approximately 0.5-1.1 m above the seabed. Figure 36 shows that the majority of epifauna occur approximately 0.4-1.5 m above the seabed. Therefore, it is likely that hydrodynamic flow around the structure between 0.5-1.1 m above the seabed, for the coastal defence groyne, and 0.5-1.5 m above the seabed, for Southwold pier pile, would differ from areas below and above these points.

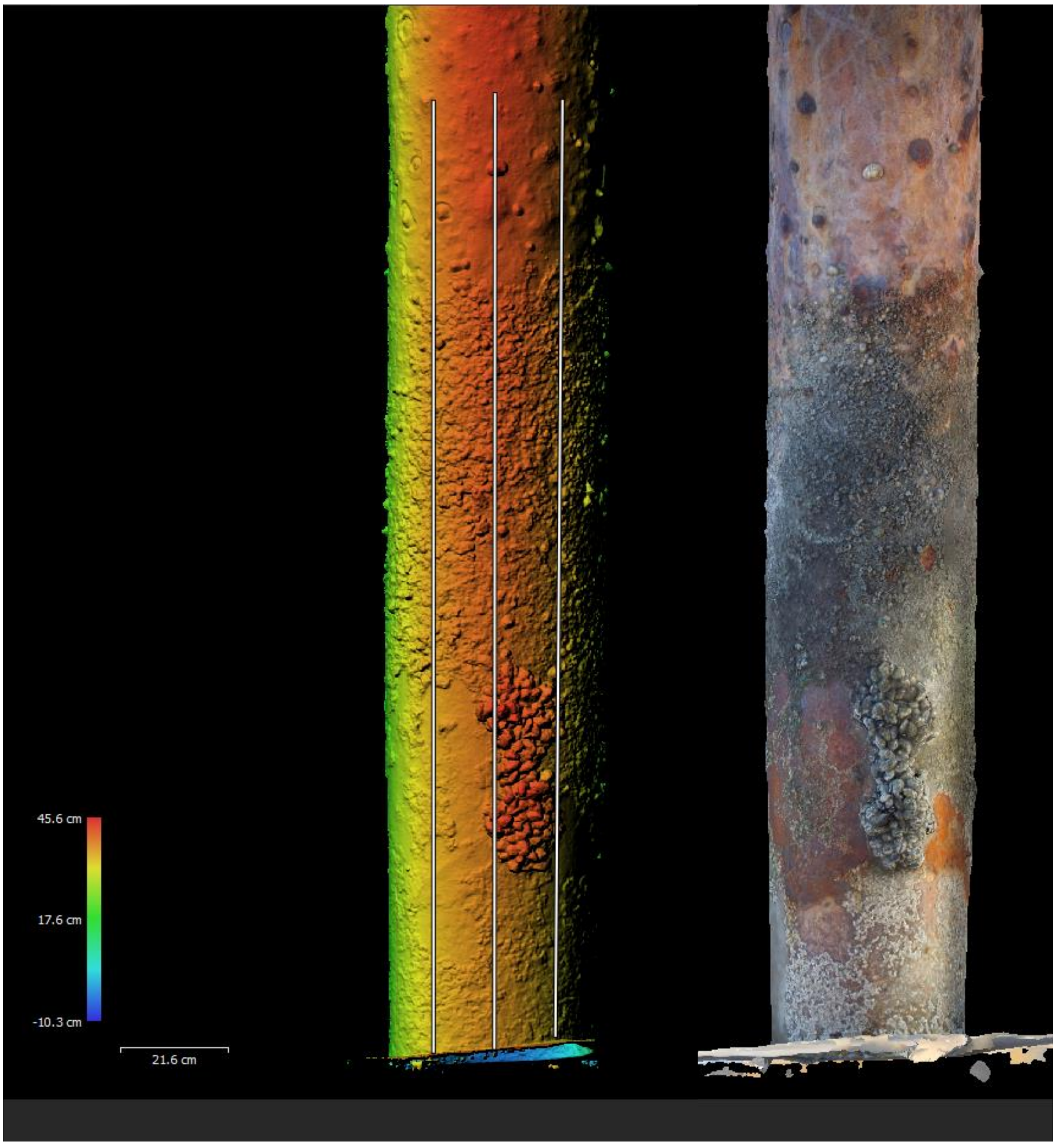

Figure 36 Photogrammetry render showing one side of the Southwold pier pile. The image on the left shows the deviation from the mean thickness in cms (red > mean, green and blue < mean as shown by the vertical scale in the left corner). The image on the right shows the original images of the surface merged. The horizontal scale bar in the left had corner indicates size. It should be noted, when interpreting these results, that the deviation from the mean thickness has been overestimated due to the curvature of the pile.

The photogrammetry results demonstrate the potential for such techniques to assist not only in quantifying surface roughness, but also in determining spatial variation in colonisation. The technique would allow for the thickness of communities on surfaces at different orientations and depths to be quantified and compared without removing epifauna from the surface in scrape samples. Variability in the thickness of biomass on the structure can also influence fatigue of the structure (Martinez-Luengo et al., 2017). Thus, photogrammetry may also be used to improve estimates of fatigue in offshore wind turbines due to colonisation.

5.7 Conclusion

This study has demonstrated the potential for natural capital assessments to provide a means of assessing the effects of offshore developments on ecosystems and the benefits they provide. This approach differs from the current EIA framework which is focused on identifying potential impacts issue by issue. Rather, through the natural capital approach emphasis is placed on changes in natural assets at a system level in an integrated way, in terms of extent, quality and quantity, and the flow of ecosystem services. Also, risks to natural capital and ecosystem services are identified. By performing a natural capital assessment, trade-offs between potential impacts and benefits can be incorporated in the decision-making process.

However, this assessment highlighted that marine survey procedures that meet the criteria for an EIA are not adequate to accurately assess natural capital. Moreover, there was insufficient information regarding natural capital from similar habitats that could be applied as proxies. This proved to be a limiting factor. As potential ways to help reduce the limits by collecting data appropriate to this type of analysis were suggested in this chapter.

Chapter 6 Discussion

6.1 Key findings and conclusions

A better understanding of the multifaceted risks associated with rising levels of atmospheric CO_2 has been a driving force behind renewable energy investment. Offshore wind energy has seen rapid growth; the installed capacity of OWFs rose from 0.8 GW in 2006 to 18.5GW in 2018 (WindEurope, 2019). By 2030 OWFs are expected to contribute more than 10% of Europe's energy (around 140 GW).

As offshore wind continues to develop, future projects are set to exceed current installed capacity and occupy a substantial area of the seabed. Based on their external boundaries (figure 11), projects that are authorised, planned, or under construction are expected to cover an area of approximately 22,000 $km^{2,}$ which represents more than a tenfold increase in surface coverage. With a total area of 575,300 km^2 (Knijn et al., 1993) on first glance it would appear that any change may have little effect over the scale of the whole North Sea. However, the southern North Sea has hydrographic circulation that is decoupled from the northern North Sea, which effectively bounds the region (Hjøllo et al., 2009; Otto, 1990) and the seabed is not homogenous (Bartholomä, 2006; Coolen et al., 2015; Dederer, 2016; S. Degraer et al., 2008; Kühne and Rachor, 1996; Markert et al., 2013; Schrieken et al., 2013). The engineering priorities of soft sediment for pile driving mean they are associated with this particular seabed type (and habitat from an ecological perspective) and so OWFs are not uniformly distributed.

Given the scale of development there will be considerable modification of benthic ecosystems in soft sediment areas of the North Sea and globally. The aim of this is research was to understand how modification of the benthic environment by offshore wind farms (OWFs) influence ecosystem services and natural capital.

6.1.1 Linking biodiversity with ecosystem services

Ecosystem services have been defined as goods and benefits that humanity receives from nature. They are typically identified as provisioning (e.g. food), regulating (e.g. carbon sequestration), cultural (e.g. tourism and recreation) and supporting (e.g. nutrient cycling). A crucial aspect of ecosystem services is that they emphasise natural assets as components of wealth, wellbeing and sustainability. In recent decades they have become a major area of research, development and policy attention. Notably, they provide a platform through which complex environmental issues can be presented in a tangible way which adds weight in decision making processes.

Several recent studies have considered the potential for OWFs to effect the delivery of ecosystem services (Busch et al., 2011; Hattam et al., 2015; Mangi, 2013; Wilding et al., 2017). Direct effects of OWFs on ecosystem services relate to the influence of physical changes to the habitat and have been considered in the literature. For example, wind turbines obstructing fishing trawlers is a direct effect that can promote the recovery of fish stocks. Indirect effects relate to the influence of epibenthic communities colonising structures, and have not been fully considered. For this reason, I reviewed published literature to identify functional pathways through which epibenthic communities may influence ecosystem services (chapter 2). I performed a keyword search in Scopus and google scholar using terms such as ‘environmental impacts of offshore wind farms’, ‘marine benthic biodiversity and ecosystem services’ and ‘biofouling offshore on wind turbines’. Based on the findings of the literature review I developed a conceptual model which illustrated pathways through which epibenthic communities on turbine substructures could be linked with the delivery of ecosystem services (figure 10). For example, epibenthic communities were linked with biogeochemical reactions that can remediate waste water. Thus a change in the biomass and biodiversity of suspension-feeding species has the potential to remediate waste and enhance water quality.

In developing the conceptual model, gaps in current knowledge were identified. From what is currently understood we can determine possible routes of change but the direction and magnitude of changes were not clear. For instance, energy and nutrient cycling could be modified by epibenthic communities on the structures, but it is not clear if the effects would be positive or negative. Nor is it clear whether effects felt close to the wind turbine would propagate through the OWF, or across the region.

6.1.2 Biodiversity change and ecosystem functioning

Whilst differences in biodiversity between natural reefs and artificial structures has been the subject of a number of studies (Ambrose and Swarbrick, 1989; Bulleri and Chapman, 2004; Knott et al., 2004; Perkol-Finkel et al., 2006; Sanabria-fernandez et al., 2018) the results have been inconclusive. As well, studies on the differences in biodiversity between artificial structures and soft sediments are absent from the literature. Offshore wind turbines introduce hard substrate and an intertidal zone to the offshore environment. Further they provide a greater surface area than their footprints occupy. Therefore, OWFs have the potential to increase biomass and alter community structure. The new structures may be occupied by epibiota ordinarily unable to colonise offshore environments. Several taxa recorded on the offshore platforms are typically associated with intertidal and coastal ecosystems, such as *Semibalanus balanoides* and the invasive splash midge *Telmatogeton japonicus*.

Whether local benthic communities would be altered by OWFs is uncertain. Moreover, whether potential changes in biodiversity would correspond to changes in ecosystem functioning is unknown. Ecosystem services are largely by-products of ecosystem functions and processes. Determining if biodiversity would change due to an OWF, and subsequently whether differences in biodiversity translate to differences in function, is necessary to understand the direction and magnitude of indirect effects on ecosystem services.

Multivariate analysis was performed on existing community data from soft sediments, rock reefs and artificial energy structures. In the first step, community structure, quantified in terms of beta (β) diversity, was compared (chapter 3). The data was collected by different researchers, and different sampling methods (scrape sampling, grab sampling, drop down camera), sizes and metrics (abundance, presence/absence, percentage coverage of substrate) were used. As such, prior to analysis all data was converted to presence/absence. Non-metric multidimensional scaling (NMS) was employed to visualise the patterns in community structure between sites. Points in the ordination plots (figure 19-figure 24) represent samples, where colour and shape differentiate sites. The distance between points in the plots corresponds to similarity in their community structure, whereby those that have greater similarity are plotted closer together. Nonmetric multidimensional scaling was considered appropriate as it is non-parametric and makes few assumptions about the nature of the data.

The evidence from the NMS indicated some clear differences in epibenthic communities between habitats. For example, communities from the platforms (P2-4) appeared similar, and differed from the rock reef (R2) and soft sediment (S1-3) (figure 21-figure 24). R1 however appeared more similar to the platforms than to R2, and R2 appeared more similar to the soft sediment sites than R1.

Whilst NMS is a useful tool for visualising patterns in complex multivariate data it does not offer a formal hypothesis test. Thus, it is not able to ascertain if the differences observed are greater that they could be by chance. As such, the NMS analysis was followed up with permutational analysis of variance (PERMANOVA) to determine whether differences observed were statistically significant. The results of the PERMANOVA indicated that differences in community structure between offshore energy platforms, soft sediments and rocky reefs were significant ($P < 0.05$) (table 4 and table 6).Therefore, considering the scale of deployment, we could expect biodiversity to change following the installation of an OWF.

Measures of biodiversity do not encompass ecosystem function directly. Rather, functional changes should take into account changes in the expression of biological traits (behavioural, morphological and life history characteristics) of species. Biological traits analysis (BTA) is a multivariate tool that has emerged as an approach for evaluating ecosystem functioning across whole assemblages. Through BTA taxonomic diversity is reduced to functional diversity. Thus, the taxonomic analysis performed in chapter 3 was extended using BTA to determine if changes in taxonomic diversity would lead to changes in functional diversity (chapter 4). It should be noted that a requirement of BTA is that component taxa be quantified, either in terms of abundance or biomass. As such, a subset of the full data for which the abundance of component taxa was available was used.

It was found that, despite significant differences in community composition, differences in trait expression were not significant for the most dominant taxa (group A) (appendix E, figures E-1 – E-11). There were significant differences in trait expression amongst less dominant taxa for a few traits. For group B, the second most common taxa, differences in feeding modes (figure 27) were statistically significant ($P < 0.05$) based on the Monte-Carlo test (table F-2). For group C and D, which included less-common taxa, differences were significant for longevity (figure 28 and table F-3) and larval duration (figure 29 and table F-4) respectively. However, it is likely the effects of these differences on ecosystem services would be muted by effects of trait expression amongst the dominant taxa.

The results of this study indicate that despite differences in community composition between natural and artificial habitats biological trait expression is generally similar. As such, there is little evidence ecosystem functioning would differ between the communities. This finding suggests that different taxa between habitats fulfil similar functional roles. It can be posited, therefore, that epibenthic communities on wind turbine substructures would support ecosystem services at similar levels to communities from natural habitats.

It is notable, that by introducing new habitat and biodiversity OWFs may generate ecological resilience. High biodiversity could increase the likelihood that multiple species that exhibit similar traits and perform similar processes would be present. This would provide biological redundancy which protects against changes to ecosystem function (Duarte, 2000; Levin, 1999; Levin and Lubchenco, 2008; Palumbi et al., 2009). For instance, dominant taxa may show declines following disturbance or a change in environmental conditions. In a system with high biodiversity there is a greater likelihood that other less-common taxa would become more dominant as competition declines or environmental conditions change. It has been demonstrated that systems with high biodiversity have greater resistance to disturbance (Gamfeldt et al., 2015; Lefcheck et al., 2015; Purvis and Hector, 2000) and faster rates of recovery (Worm et al., 2006).

6.1.3 Potential for natural capital assessments in marine benthic habitats

Whilst there is considerable concern regarding the environmental impact of OWFs, particularly during the construction phase, there are potential benefits to ecosystem services during the operational phase. Under current regulations, an EIA is required for offshore wind energy developments. As part of the of an EIA, baseline surveys are performed to ascertain the current conditions of the habitat and the taxa present. In essence, EIAs provide a snapshot of the ecosystem to in order to identify the potential impacts from the proposed development. However, EIAs have been criticised for emphasising negative impacts and being less effective at evaluating positive and non-local benefits.

A natural capital assessment (NCA) offers an additional approach for planning and continued environmental monitoring that incorporates both positive and negative changes across multiple scales. There is a consensus that the maintenance of natural capital, biotic and abiotic elements of nature which produce goods and services to people (figure 32), is necessary for sustainable development. The intent of NCAs is to support decision making in respect to the sustainable use of the natural environment.

An NCA was conducted for Thanet OWF (chapter 5) to determine likely changes to natural capital following the installation of multiple turbine structures. The foundation of an NCA is a natural capital asset register, which provides an inventory of natural resources within the defined area, in this case Thanet OWF development site (TDS). Ideally, the asset register would demonstrate the quantity, quality and distribution of natural assets. The asset register was evaluated with the benthic base-line survey data along with published data and technical reports from the Thanet area (Pearce et al., 2014; Marine Ecological Surveys Ltd, 2008; Thanet Offshore Wind Ltd, 2005), which represented natural capital prior to the OWF installation. In absence of post-installation monitoring data epibenthic community data from platforms P1-4 (figure 31) were included to represent epibenthic communities on wind turbine substructures. Based on the asset register the likely flow of services before and after the installation was evaluated (table 12). Services were presented in relation to natural capital assets to which they may be directly or indirectly linked. For example, it determined that biogenic structures existed prior to the installation of the OWF that would generate habitat and provide opportunities for feeding and shelter for commercial species. Following the installation of Thanet OWF, the turbine substructures would also provide habitat and shelter and could support the recovery of biogenic structures by obstructing trawling. Subsequently, a comparative assessment of risks to services was produced (table 13). For instance, it was established that the installation of the OWF presents new risks, such as electromagnetic fields (EMF), hydrodynamic flow changes, turbine maintenance and, at the end of the operational life of the turbines, decommissioning. Although, due to a lack of empirical evidence, confidence in the assessment of these risks was considered to be low. On the other hand, by providing a physical obstruction the OWF can reduce the risks from fishing activities and support commercial fisheries through overspill from within the OWF. Due to greater availability of empirical evidence, confidence in the assessment of the risk of fishing was considered to be high.

Informed by the assessment of services and the asset risk register, a number of options for developing and managing natural capital within the offshore wind farm were presented. Firstly, there is scope for installing further habitat that would likely support communities more similar to those on wind turbine foundations. Some developers have taken the opportunity to use large stones to build artificial reefs within the extent of an OWF (Orsted, 2019). Were this to been done at Thanet OWF rock reefs would further increase habitat heterogeneity and create shelter and feeding opportunities for demersal megafauna. In addition, rock scour protection could be placed around turbines in Thanet OWF and, should it receive approval, the turbines in the Thanet extension. Both of these options could support lobster and crab populations which thrive in rocky habitat. Use of the turbine foundations to support or anchor mussel and oyster aquaculture systems has also been suggested. As such, Thanet OWF could foster alternative fisheries that do not utilise destructive mobile fishing which would provide economic benefit to a displaced fishing community.

In addition, as with installing OWFs, decommissioning is highly destructive to the seabed and can present risks to natural capital and ecosystem services. Further, in decommissioning the structures, colonising communities, and the benefits received from them, will be removed. Thus, alternatives to decommissioning, for example, the repowering of turbines to continue generating energy, should be considered. This may have the added advantage of preventing the need for another OWF to be constructed, thus impacting another site. Yet, current legal obligations call for the complete removal of structures and for the site to be returned to its pre-installation condition. Whilst well intentioned, this policy may be short sighted. It cannot be guaranteed that removal of the structures would return the TDS to its pre-installation condition. Further, following generations of intensive fishing the pre-installation TDS was an impacted state. Given OWFs have the potential to raise natural capital and support ecosystem services, there is scope for revisiting current legislation.

Data limitations proved to be a major challenge in conducting the NCA of Thanet OWF. Data collected as part of an EIA lack the information at relevant ecosystem scales to discern trends in natural capital over time. In forming the asset register, records of biogenic reefs, formed by *Mytilidae*, *Sabellaria spinulosa* and *Lanice conchilega*, were mapped (figure 34) and the quality of the reefs and their extent was discussed. It was found, that only a relatively small portion of the wind farm extent had been surveyed. Thus, the condition and extent of biogenic structures throughout the TDS was largely unknown. Further, there was a lack of suitable proxies, habitats with similar biophysical components or processes, which could provide insights in absence of more complete datasets. Alternative survey methods aimed at providing long-term pre- and post-installation community data, were suggested. For instance, temporary structures, based on the experimental arrays presented in chapter 1, could mimic surfaces provided by the wind farm substructures. Placed inside the planned wind farm extent, the structures would be colonised by communities that are likely to be similar to those that would colonise the wind turbine substructures. These structures can be deployed several years prior to the construction of the turbines and be left in place following construction. They could therefore provide evidence of the expected community development and succession on the substructures and provide fixed points for repeated sampling, allowing longer term trends to be established.

6.2 Contribution

There is a growing realisation that ecosystem services, obtained from natural capital, are of vital importance to the human wealth, wellbeing and the sustainable use of resources. Through this work, the potential effects of modifying natural capital were emphasised in the context of offshore wind energy. In recent years, direct effects from OWFs on ecosystem services have been documented, whilst indirect effects, relating to biodiversity change, are less certain and have received limited attention.

The evidence presented here supports the idea that the installation of offshore wind turbines in regions of predominantly soft sediment habitat would lead to changes in local benthic biodiversity. Yet, there is little evidence that changes in biodiversity would subsequently affect ecosystem functioning. Differences in expression of biological traits by dominant taxa were not found to be significant despite statistically significant differences in community composition. As ecosystem services are largely a product of ecosystem functioning the results suggest that epibenthic communities that colonise turbines would support ecosystem services at similar levels to those in natural habitats. This finding implies that different species between the communities perform analogous ecological roles.

The results of the analysis notwithstanding, drawing conclusions on how ecosystem functioning would be affected over greater scales, such as across an OWF, or over a region with multiple OWFs, should be carefully considered and justified. Biological traits analysis was performed on a subset of data for which abundance was available. As a result, a number of taxa, particularly colonial species, were excluded from the analysis. Further, the availability of information on biological traits was uneven as certain taxa and traits had received less attention in the literature. In addition, data from epibenthic communities sampled from offshore energy platforms were used as surrogates for offshore wind turbines in this work. It should be noted that these structures differ from offshore wind turbines in a number of ways. For example, based on their footprint and distances between turbines, OWFs can cover a larger area and have greater connectivity than platforms. Explicitly, the effects of offshore wind turbines on ecosystems are likely to be cumulative and influenced by neighbouring turbines and associated assemblages. In respect to oil and gas platforms (such as P2-5) one should also consider their function compared to wind turbines. Stressors associated with oil and gas platforms, such as noise levels or contaminants, would differ from those associated with wind turbines. Nonetheless, given the findings in this study the potential for OWFs, through the provision of novel hard substrate and their ability to alter the benthic environment, to modify community structure and raise natural capital is evident. This is highly relevant given the emergence of new technologies, such as floating offshore wind turbines and wave and tidal stream, that are expected to contribute to renewable energy generation in the future (European Commission, 2014).

This work supports that of others (Froján et al., 2016; Hooper et al., 2017b; Papathanasopoulou et al., 2015; Wilding et al., 2017) in demonstrating a need for monitoring programmes that consider developments in the context of ecosystem service provision. Surveys designed to meet the requirements of the EIA framework do not currently meet this need. For instance, grab samples cover only a very small area. Further, at the TDS, resampling was not performed in the same locations in following years. Thus, whilst benthic data from the EIA gave an indication of species present, trends in extent, quality and quantity of natural assets could not be reasonably determined.

Temporary structures can assist in pre and post-installation monitoring that is inclusive of ecosystem services. The EIA process may take up to 3 years (The Crown Estate and Catapult Offshore Renewable Energy, 2019); deploying temporary structures throughout a development site during this period would provide an indication of how natural capital may change following the installation of an OWF. Further, by marking locations for repeated sampling temporary moorings can assist in the identification of trends and patterns of succession.

A natural capital perspective towards environmental monitoring and management within an OWF offers an alternative framework that centres on the provision of ecosystem services. Trade-offs between risks and benefits can be evaluated and included in the decision-making process; new evidence may be used to revise current practices and legislation. Subsequently, in addition to acting to mitigate risks, action can be taken to maximise benefits.

6.3 **Further work**

The work presented here has provided a firm basis on which to link OWFs with natural capital and ecosystem services. Yet, it would be inappropriate to assume that epibenthic communities on platforms would equally represent those on all turbines. It is expected that turbines would influence environmental conditions across the OWF. For example, as currents travel through an OWF the hydrodynamic regime around turbines upstream, on the edge of the OWF, would differ from that in the centre (chapter 4). Environmental variability may lead to variability in processes and ecosystem functioning within the OWF. Understanding trait responses to variability in environmental conditions within an OWF may provide a more accurate picture of the provision and resilience of ecosystem services. To better assess the influence of OWFs on natural capital and ecosystem services, an analysis of natural capital change and ecosystem functioning, which is inclusive of spatial and temporal variability in environmental conditions, should be performed with epibenthic community data from full scale OWFs.

Addressing paucity in benthic data is an important step for future studies into ecosystem function. For other systems, where gaps in data exist, those from similar habitats were applied as proxies. This strategy could not be used in the case of marine benthic systems. Thus, closing benthic data gaps would produce proxies through which functional change and the effects on ecosystem services could be better estimated. Data collection should be relevant to determining trends in extent, quality and quantity of natural capital. Grab sampling is limited in terms of the area and substrate that can be sampled (Beisiegel et al., 2017; Marine Ecological Surveys Ltd, 2008). To be useful in determining extent, quality and quantity of natural capital it should be conducted at regular intervals throughout the site, and supplemented with alternative methods, such as camera systems, where the substrate is too hard to sample. Grab sampling should also be combined with acoustic survey methods; multibeam echosounder systems (MBES) and sidescan sonar (SSS), could present an efficient and cost-effective means of mapping benthic natural capital. Both MBES and SSS can provide continuous coverage of large areas of seabed in fine detail (Coolen et al., 2015; Degraer et al., 2008; Markert et al., 2013; Micallef et al., 2012; Pearce et al., 2014). Indeed, Pearce et al (2014) demonstrated the effectiveness of SSS in mapping *S. spinulosa* reefs within Thanet OWF. Where physical samples are collected, quantitative metrics should be used consistently. For the taxonomic analysis presented in chapter 3, data was reduced to presence/absence as metrics available in the datasets differed. The information available on the structure and dynamics of communities based on presence/absence data is limited. Due to the prevalence of colonial taxa in benthic systems, a measure of biomass may be more suitable.

Deploying temporary structures in future wind energy development sites could provide targeted insight into cross-discipline questions related to the development of communities on turbine substructures. The experimental design presented in section 1.3.1 was intended to explore variation in colonisation due to spatial orientation and the development of corrosion pits on steel plates mounted inside the frames simultaneously. The design could be adapted further to answer other ecological and engineering questions, including how artificial structures would alter natural capital and affect ecosystem functioning. Sections of the deployment could be removed so that communities could be sampled, and photographs can be taken, above the waterline, reducing complexity and risks in the process. Further, photogrammetry of temporary structures could be used to quantify surface roughness to evaluate computational fluid dynamics (CFD) models. Using CFD engineers may better understand how epibenthic communities on the structure may influence drag and inertia. This may be of particular importance to floating turbines and their moorings. Also understanding how turbines and colonising communities' affect hydrodynamic flow around structures and through the OWF would be informative in understanding the extent of plumes and their influence on the surrounding habitat.

There is much more to understand about the interaction between OWF and the environment. A systematic approach to addressing outstanding questions will enable the science to better support the further expansion of OWFs across the globe and feed into questions associated with other marine energy structures in order to promote an integrated understanding of the changes that will inevitably result. This is particularly relevant given the emergence of new energy technologies such as floating wind turbines and the prospect of large-scale installations of wave and tidal devices which are likely to bring similar changes as well as having their own effects.

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Appendices

Appendix A R code community analysis

The following R code was written to analyse community data. The hashtag (#) symbol signifies in R that the text that follows is a note to the operator. Thus, R will not run a line of text that is preceded by a #. These notes have been included here for clarity of the code.

A.1 Datasets

A.1.1 Exploratory analysis datasets (Chapter 3.3.1)

The following R code imported data sets in to R for the exploratory analysis of community data.

```
# Community data for figure 6
RAS <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\RAS
BD final.csv", row.names=1, header=TRUE)
# Community data for figure 7
RAS_BP <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity
analysis\\RAS\\RAS bubble plot final.csv", header=TRUE)
#Heatmap data for figures 8a-g (HM1-7 respectively)
HM1 <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\HM1
final.csv", header=TRUE)
HM2 <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\HM2
final.csv", header=TRUE)
HM3 <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\HM3
final.csv", header=TRUE)
HM4 <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\HM4
final.csv", header=TRUE)
HM5 <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\HM5
final.csv", header=TRUE)
HM6 <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\HM6
final.csv", header=TRUE)
HM7 <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\HM7
final.csv", header=TRUE)
```

A.1.2 Multivariate analysis datasets

```
# RA: combined rock reef and platform community dataset (presence/absence)
RA <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\RA
BD.csv", row.names=1, header=TRUE)
# RS: combined rock reef and soft sediment community dataset (presence/absence)
RS <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\RS BD
final.csv", row.names=1, header=TRUE)
#AS: combined platform and soft sediment community dataset (presence/absence)
```

```
AS <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\AS BD
final.csv", row.names=1, header=TRUE)
#RAS_SN: List of platform, rock reef and soft sediment site names
RAS_SN <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity
analysis\\RAS\\RAS site names final.csv", header=TRUE)
#RASAD: Combined platform, rock reef and soft sediment community data formatted for
           PERMANOVA
RASAD <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\RAS
           BD adonis final.csv", row.names=1, header=TRUE)
#RASAD_SN: List of platform, rock reef and soft sediment site names formatted for
                PERMANOVA
RASAD_SN <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity
                analysis\\RAS\\RAS site names for adonis.csv", header=TRUE)
#RA_SN: List of platform and rock reef site names formatted for PERMANOVA
RA_SN <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\RA
site names final.csv", header=TRUE)
#RS_SN: List of rock reef and soft sediment site names formatted for PERMANOVA
RS_SN <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\RS
site names final.csv", header=TRUE)
#AS_SN: List of platform and soft sediment site names formatted for PERMANOVA
AS_SN <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\3. Biodiversity analysis\\RAS\\AS
site names final.csv", header=TRUE)
```

A.2 R code for exploratory analysis (Chapter 3.3.1)

```
#Set default theme for ggplot to black and white:
      theme_set(theme_classic() + theme(legend.title=element_blank(),
      legend.key.height=unit(2, "cm"),
      panel.grid.major=element_blank(), panel.grid.minor=element_blank(),
      panel.background=element_blank(), axis.line=element_line(colour="black"),
      axis.text.x=element_text(size=9, angle=0, vjust=0.3), axis.text.y=element_text(size=9)))

#Figure 15:
Bar1 <- ggplot(RAS_PL, aes(x=Phylum, y=Percent.of.taxa, fill=Substrate),
order=as.numeric(Substrate) ) +
  geom_bar(stat="identity", position="dodge") + coord_flip() + ylab("Percent of Taxa") +
xlab("") +
  scale_fill_grey(start=0.5, end=0.8) + guides(fill=guide_legend(reverse=TRUE)) +
  scale_y_continuous(limits=c(0,40)) +
  theme(legend.title=element_blank(),
      legend.text=element_text(size=11),
      panel.grid.major=element_blank(),
      panel.grid.minor=element_blank(),
      panel.background=element_blank(),
      axis.text.x=element_text( angle=0, hjust=0.5),
      axis.text.y=element_text(size=11),
      axis.line=element_line(colour="black"))
Bar1
```

```
#Figure 16:
Bubble1 <- ggplot(RAS_BP, aes(x=Substrate, y=Site, size=Percent)) +
  geom_point(shape=21, colour="black", fill="grey") +
  scale_size_area(max_size=60, guide=FALSE) +
  geom_text(aes(y=as.numeric(Site)-sqrt(Percent)/22, label=Percent), vjust=2.5, hjust=0.5,
colour="black", size=6) +
  theme(panel.grid.major=element_blank(),
        panel.grid.minor=element_blank(),
        panel.background=element_blank(),
        axis.title.x=element_blank(),
        axis.title.y=element_blank(),
        axis.text=element_text(size=14),
        axis.line=element_line(colour="black"))
Bubble1

#Figure 17a-g:
Heatmap1 <- ggplot(HM1, aes(x=Site, y=Taxa, fill=Rank)) +
  geom_tile(colour="white", size=0.25) + labs(x="", y="") +
  scale_fill_distiller(palette="Greys", direction=1, breaks=c(0,1,2,3,4,5,6,7,8,9))
Heatmap1
Heatmap2 <- ggplot(HM2, aes(x=Site, y=Taxa, fill=Rank)) +
  geom_tile(colour="white", size=0.25) + labs(x="", y="") +
  scale_fill_distiller(palette="Greys", direction=1, breaks=c(0,1,2,3,4,5,6,7,8,9))
Heatmap2
Heatmap3 <- ggplot(HM3, aes(x=Site, y=Taxa, fill=Rank)) +
  geom_tile(colour="white", size=0.25) + labs(x="", y="") +
  scale_fill_distiller(palette="Greys", direction=1, breaks=c(0,1,2,3,4,5,6,7,8,9))
Heatmap3
Heatmap4 <- ggplot(HM4, aes(x=Site, y=Taxa, fill=Rank)) +
  geom_tile(colour="white", size=0.25) + labs(x="", y="") +
  scale_fill_distiller(palette="Greys", direction=1, breaks=c(0,1,2,3,4,5,6,7,8,9))
Heatmap4
Heatmap5 <- ggplot(HM5, aes(x=Site, y=Taxa, fill=Rank)) +
  geom_tile(colour="white", size=0.25) + labs(x="", y="") +
  scale_fill_distiller(palette="Greys", direction=1, breaks=c(0,1,2,3,4,5,6,7,8,9))
Heatmap5
Heatmap6 <- ggplot(HM6, aes(x=Site, y=Taxa, fill=Rank)) +
  geom_tile(colour="white", size=0.25) + labs(x="", y="") +
  scale_fill_distiller(palette="Greys", direction=1, breaks=c(0,1,2,3,4,5,6,7,8,9))
Heatmap6
Heatmap7 <- ggplot(HM7, aes(x=Site, y=Taxa, fill=Rank)) +
  geom_tile(colour="white", size=0.25) + labs(x="", y="") +
  scale_fill_distiller(palette="Greys", direction=1, breaks=c(0,1,2,3,4,5,6,7,8,9))
Heatmap7
```

A.3 R code for multivariate Data Analysis (Chapter 3.3.2)

A.3.1 R code for non-metric multidimensional scaling (NMS)

```
#NMS comparison of rock rees and soft sediments
RS3D <- metaMDS(RS, k=3, trymax=1000, distance="jaccard", autotransform=TRUE,
noshare=TRUE)
RS3D
#Figure 19 and 20
RA_SN$NMDS1<-RA3D$points[ ,1]
RA_SN$NMDS2<-RA3D$points[ ,2]
RA_SN$NMDS3<-RA3D$points[ ,3]

veganCovEllipse <- function (cov, center=c(0, 0), scale=1, npoints=100)
{
  theta <- (0:npoints) * 2 * pi/npoints
  Circle <- cbind(cos(theta), sin(theta))
  t(center + scale * t(Circle %*% chol(cov)))
}

df_ell.RA.site.code_1.2 <- data.frame()
for(g in levels(RA_SN$Site.code)){
        df_ell.RA.site.code_1.2 <- rbind(df_ell.RA.site.code_1.2,
        cbind(as.data.frame(with(RA_SN [RA_SN$Site.code==g,],
        veganCovEllipse(cov.wt(cbind(NMDS1,NMDS2),wt=rep(1/length(NMDS1),length(NMDS
        1)))$cov,center=c(mean(NMDS1),mean(NMDS2)))))
                                        ,Site.code=g))
}

NMDS.mean=aggregate(RA_SN[ ,c("NMDS1", "NMDS2")],
             list(group=RA_SN$Site.code), mean)
(RA.nmds.gg1 <- ggplot(data=RA_SN, aes(y=NMDS2, x=NMDS1)) +
   geom_path(data=df_ell.RA.site.code_1.2, aes(x=NMDS1, y=NMDS2, group=Site.code,
   alpha=Site.code)) +
   scale_alpha_manual(guide=FALSE,values=c(1, 1, 1, 1, 1, 1, 1)) +
   geom_point(aes(shape=Site.code, colour=Site.code), size=5) +
   annotate("text",x=NMDS.mean$NMDS1,y=MDS.mean$NMDS2,label=NMDS.mean$group) +
   scale_shape_manual(values=c(0,1,2,5,6,9,13)) +
   theme_bw() +
   theme(panel.grid.major=element_blank(),
      panel.grid.minor=element_blank()))

df_ell.RA.site.code_1.3 <- data.frame()
for(g in levels(RA_SN$Site.code)){
        df_ell.RA.site.code_1.3 <- rbind(df_ell.RA.site.code_1.3,
        cbind(as.data.frame(with(RA_SN [RA_SN$Site.code==g,],
        veganCovEllipse(cov.wt(cbind(NMDS1,NMDS3),wt=rep(1/length(NMDS1),length(NMDS
        1)))$cov,center=c(mean(NMDS1),mean(NMDS3)))))
                                     ,Site.code=g))
```

```
}

NMDS.mean=aggregate(RA_SN[ ,c("NMDS1", "NMDS3")],
            list(group=RA_SN$Site.code), mean)
(RA.nmds.gg1 <- ggplot(data=RA_SN, aes(y=NMDS3, x=NMDS1))  +
  geom_path(data=df_ell.RA.site.code_1.3, aes(x=NMDS1, y=NMDS3, group=Site.code,
  alpha=Site.code)) +
  scale_alpha_manual(guide=FALSE,values=c(1, 1, 1, 1, 1, 1, 1)) +
  geom_point(aes(shape=Site.code, colour=Site.code), size=5)
  annotate("text",x=NMDS.mean$NMDS1,y=MDS.mean$NMDS3,label=NMDS.mean$group) +
  scale_shape_manual(values=c(0,1,2,5,6,9,13)) +
  theme_bw() +
  theme(panel.grid.major=element_blank(),
      panel.grid.minor=element_blank()))

#NMS comparison of platforms and soft sediments
AS3D <- metaMDS(AS, k=3, trymax=1000, distance="jaccard", autotransform=TRUE,
noshare=TRUE)
AS3D
#Figure 21 and 22
RS_SN$NMDS1<-RS3D$points[ ,1]
RS_SN$NMDS2<-RS3D$points[ ,2]
RS_SN$NMDS3<-RS3D$points[ ,3]

veganCovEllipse <- function (cov, center=c(0, 0), scale=1, npoints=100)
{
 theta <- (0:npoints) * 2 * pi/npoints
 Circle <- cbind(cos(theta), sin(theta))
 t(center + scale * t(Circle %*% chol(cov)))
}
df_ell.RS.site.code_1.2 <- data.frame()
for(g in levels(RS_SN$Site.code)){
        df_ell.RS.site.code_1.2 <- rbind(df_ell.RS.site.code_1.2,
        cbind(as.data.frame(with(RS_SN [RS_SN$Site.code==g,],
        veganCovEllipse(cov.wt(cbind(NMDS1,NMDS2),wt=rep(1/length(NMDS1),length(NMDS
        1)))$cov,center=c(mean(NMDS1),mean(NMDS2)))))
                                   ,Site.code=g))
}

NMDS.mean=aggregate(RS_SN[ ,c("NMDS1", "NMDS2")],
            list(group=RS_SN$Site.code), mean)
(RS.nmds.gg1 <- ggplot(data=RS_SN, aes(y=NMDS2, x=NMDS1)) +
  geom_path(data=df_ell.RS.site.code_1.2, aes(x=NMDS1, y=NMDS2, group=Site.code,
  alpha=Site.code))+
  scale_alpha_manual(guide=FALSE,values=c(1, 1, 1, 1, 1, 1, 1)) +
  geom_point(aes(shape=Site.code, colour=Site.code), size=5) +
  annotate("text",x=NMDS.mean$NMDS1,y=MDS.mean$NMDS2,label=NMDS.mean$group) +
  scale_shape_manual(values=c(0,1,2,5,6,9,13)) +
```

```
   theme_bw()+
   theme(panel.grid.major=element_blank(),
        panel.grid.minor=element_blank()))

df_ell.RS.site.code_1.3 <- data.frame()
for(g in levels(RS_SN$Site.code)){
            df_ell.RS.site.code_1.3 <- rbind(df_ell.RS.site.code_1.3,
            cbind(as.data.frame(with(RS_SN [RS_SN$Site.code==g,],
            veganCovEllipse(cov.wt(cbind(NMDS1,NMDS3),wt=rep(1/length(NMDS1),length(NMDS
            1)))$cov,center=c(mean(NMDS1),mean(NMDS3)))))
                                                    ,Site.code=g))
}

NMDS.mean=aggregate(RS_SN[ ,c("NMDS1", "NMDS3")],
                 list(group=RS_SN$Site.code), mean)
(RS.nmds.gg1 <- ggplot(data=RS_SN, aes(y=NMDS3, x=NMDS1)) +
   geom_path(data=df_ell.RS.site.code_1.3, aes(x=NMDS1, y=NMDS3, group=Site.code,
   alpha=Site.code)) +
   scale_alpha_manual(guide=FALSE,values=c(1, 1, 1, 1, 1, 1, 1)) +
   geom_point(aes(shape=Site.code, colour=Site.code), size=5) +
   annotate("text",x=NMDS.mean$NMDS1,y=MDS.mean$NMDS3,label=NMDS.mean$group) +
   scale_shape_manual(values=c(0,1,2,5,6,9,13)) +
   theme_bw() +
   theme(panel.grid.major=element_blank(),
        panel.grid.minor=element_blank()))

#NMS comparison of rock reef and platform samples
RA3D <- metaMDS(RA, k=3, trymax=1000, distance="jaccard", autotransform=TRUE)
RA3D

#Figure 23 and 24
AS_SN$NMDS1<-AS3D$points[ ,1]
AS_SN$NMDS2<-AS3D$points[ ,2]
AS_SN$NMDS3<-AS3D$points[ ,3]

veganCovEllipse <- function (cov, center=c(0, 0), scale=1, npoints=100)
{
  theta <- (0:npoints) * 2 * pi/npoints
  Circle <- cbind(cos(theta), sin(theta))
  t(center + scale * t(Circle %*% chol(cov)))
}

df_ell.AS.site.code_1.2 <- data.frame()
for(g in levels(AS_SN$Site.code)){
            df_ell.AS.site.code_1.2 <- rbind(df_ell.AS.site.code_1.2,
            cbind(as.data.frame(with(AS_SN [AS_SN$Site.code==g,],
            veganCovEllipse(cov.wt(cbind(NMDS1,NMDS2),wt=rep(1/length(NMDS1),length(NMDS
            1)))$cov,center=c(mean(NMDS1),mean(NMDS2)))))
```

```
                                         ,Site.code=g))
}

NMDS.mean=aggregate(AS_SN[ ,c("NMDS1", "NMDS2")],
        list(group=AS_SN$Site.code), mean)

(AS.nmds.gg1 <- ggplot(data=AS_SN, aes(y=NMDS2, x=NMDS1)) +
  geom_path(data=df_ell.AS.site.code_1.2, aes(x=NMDS1, y=NMDS2, group=Site.code,
  alpha=Site.code)) +
  scale_alpha_manual(guide=FALSE,values=c(1, 1, 1, 1, 1, 1, 1, 1)) +
  geom_point(aes(shape=Site.code, colour=Site.code), size=5) +
  annotate("text",x=NMDS.mean$NMDS1,y=NMDS.mean$NMDS2,label=NMDS.mean$group) +
  scale_shape_manual(values=c(0,1,2,3,5,6,9,13)) +
  theme_bw() +
  theme(panel.grid.major=element_blank(),
     panel.grid.minor=element_blank()))

df_ell.AS.site.code_1.3 <- data.frame()
for(g in levels(AS_SN$Site.code)){
      df_ell.AS.site.code_1.3 <- rbind(df_ell.AS.site.code_1.3,
      cbind(as.data.frame(with(AS_SN [AS_SN$Site.code==g,],
      veganCovEllipse(cov.wt(cbind(NMDS1,NMDS3),wt=rep(1/length(NMDS1),length(NMDS
      1)))$cov,center=c(mean(NMDS1),mean(NMDS3)))))
                                         ,Site.code=g))
}

NMDS.mean=aggregate(AS_SN[ ,c("NMDS1", "NMDS3")],
        list(group=AS_SN$Site.code), mean)
(AS.nmds.gg1 <- ggplot(data=AS_SN, aes(y=NMDS3, x=NMDS1)) +
  geom_path(data=df_ell.AS.site.code_1.3, aes(x=NMDS1, y=NMDS3, group=Site.code,
  alpha=Site.code)) +
  scale_alpha_manual(guide=FALSE,values=c(1, 1, 1, 1, 1, 1, 1, 1)) +
  geom_point(aes(shape=Site.code, colour=Site.code), size=5) +
  annotate("text",x=NMDS.mean$NMDS1,y=NMDS.mean$NMDS3,label=NMDS.mean$group) +
  scale_shape_manual(values=c(0, 1, 2, 3, 5, 6, 9, 13)) +
  theme_bw() +
  theme(panel.grid.major=element_blank(),
     panel.grid.minor=element_blank()))
```

A.3.2 R code for permutational analysis of variance (PERMANOVA) (Chapter 3.3.2)

```
#Results in table 4:
RAS.jacc <- vegdist(RAS, method="jaccard", binary=TRUE)
RASd2 <- adonis2(RAS.jacc ~ Site.code, permutations=100000, data=RAS_SN)
RASd2

#Results in table 5:
RASAD.jacc <- vegdist(RASAD, method="jaccard", binary=TRUE)
```

```
RASADd2 <- adonis2(RASAD.jacc ~ Site.code + Depth + Distance + Substrate + Depth*Substrate,
permutations=100000, data=RASAD_SN)
RASADd2
#Pairwise comparisons for PERMANOVA: the function pairwise.adonis was created by Azbizu
(2017)
pairwise.adonis <- function(x,factors, sim.function='vegdist', sim.method='jaccard', p.adjust.m
='bonferroni')
{
 library(vegan)
 co=combn(unique(as.character(factors)),2)
 pairs=c()
 F.Model =c()
 R2=c()
 p.value=c()
 for(elem in 1:ncol(co)){
  if(sim.function == 'daisy'){
   library(cluster); x1=daisy(x[factors %in% c(co[1,elem],co[2,elem]),],metric=sim.method)
  } else{x1=vegdist(x[factors %in% c(co[1,elem],co[2,elem]),],method=sim.method)}
  ad=adonis(x1 ~ factors[factors %in% c(co[1,elem],co[2,elem])], permutations=100000);
  pairs=c(pairs,paste(co[1,elem],'vs',co[2,elem]));
  F.Model =c(F.Model,ad$aov.tab[1,4]);
  R2=c(R2,ad$aov.tab[1,5]);
  p.value=c(p.value,ad$aov.tab[1,6])
 }
 p.adjusted=p.adjust(p.value,method=p.adjust.m)
 sig=c(rep('',length(p.adjusted)))
 sig[p.adjusted <= 0.05] <-'.'
 sig[p.adjusted <= 0.01] <-'*'
 sig[p.adjusted <= 0.001] <-'**'
 sig[p.adjusted <= 0.0001] <-'***'
  pairw.res=data.frame(pairs,F.Model,R2,p.value,p.adjusted,sig)
 print("Signif. codes:  0 â··***â·· 0.001 â··**â·· 0.01 â··*â·· 0.05 â··.â·· 0.1 â·· â·· 1")
 return(pairw.res)
}
# Results in table 6
pairwise.adonis(RAS, factors=RAS_SN$Site.code, sim.method="jaccard")
#Results in table 7:
pairwise.adonis(RASAD, factors=RASAD_SN$Substrate, sim.method="jaccard")
```

Appendix B Presence/absence of taxa by substrate (Chapter 3.3)

Table B-1 taxa recorded of artificial structures, rock reefs and soft sediments (● = present, ○ = absent)

Phylum	Platform	Rocky Reef	Soft Sediment
Annelida			
Oligochaeta	○	○	●
Polychaete			
Amaeana trilobata	○	○	●
Ampharete lindstroemi	○	○	●
Amphicteis midas	○	○	●
Aonides spp.	○	○	●
Aphelochaeta spp.	○	○	●
Aphrodita aculeata	○	○	●
Aricidea minuta	○	○	●
Asclerocheilus intermedius	○	○	●
Atherospio disticha	○	○	●
Capitellidae	●	●	○
Caulleriella alata	○	○	●
Chaetopterus variopedatus	●	○	○
Chaetozone zetlandica	○	○	●
Cirratulidae	○	○	●
Clymenura spp.	○	○	●
Crucigera spp.	●	○	○
Dipolydora spp.	○	○	●
Drilonereis filum	○	○	●
Echiuridae	○	○	●
Ephesiella abyssorum	○	○	●
Eteoninae	●	○	●
Euclymene oerstedi	○	○	●
Eulalia spp.	●	●	●
Eumida bahusiensis	○	○	●
Eumida sanguinea	●	○	●
Eunereis longissima	●	●	○
Eupolymnia nebulosa	○	○	●
Eusyllis blomstrandi	●	○	●
Exogone spp.	○	○	●
Filograna implexa	○	○	●
Flabelligera affinis	○	○	●
Galathowenia oculata	○	○	●
Gattyana cirrhosa	●	○	●
Glycera spp.	●	○	●

Glycinde nordmanni	○	○	●
Goniada maculata	○	○	●
Gyptis rosea	○	○	●
Haplosyllis spongicola	○	○	●
Harmothoe clavigera	●	●	○
Harmothoe extenuata	●	○	●
Harmothoe fernandi	●	●	○
Harmothoe fragilis	●	○	●
Harmothoe impar	●	●	●
Harmothoe ljungmani	●	○	○
Harmothoe viridis	●	○	○
Hesionura elongata	○	○	●
Janua heterostropha	○	○	●
Jasmineira elegans	○	○	●
Lagis koreni	○	○	●
Lanice conchilega	●	●	●
Laonice bahusiensis	○	○	●
Lepidonotus squamatus	●	●	●
Lumbrineridae	●	○	●
Lysidice spp.	○	○	●
Macrochaeta helgolandica	○	○	●
Magelona mirabilis	○	○	●
Malmgrenia spp.	○	○	●
Marphysa spp.	○	○	●
Mediomastus fragilis	○	○	●
Micromaldane ornithochaeta	○	○	●
Microphthalmus similis	○	○	●
Microspio mecznikowianus	○	○	●
Myrianida spp.	●	●	●
Mysta picta	○	○	●
Neoamphitrite spp.	○	○	●
Nephtys spp.	○	○	●
Nereis spp.	●	●	●
Nicolea venustula	○	○	●
Nicomache trispinata	○	○	●
Nothria conchylega	●	○	○
Notomastus spp.	●	○	●
Odontosyllis spp.	○	○	●
Ophelia borealis	○	○	●
Owenia fusiformis	○	○	●
Oxydromus spp.	○	○	●
Paradoneis lyra	○	○	●

Paranaitis kosteriensis	○	○	●
Paraonis fulgens	○	○	●
Perkinsiana rubra	○	○	●
Petaloproctus spp.	○	○	●
Pherusa plumosa	○	○	●
Pholoe spp.	○	○	●
Phyllodoce groenlandica	●	○	●
Phyllodoce longipes	●	○	●
Phyllodoce maculata	●	○	●
Phyllodoce mucosa	●	○	●
Phyllodoce rosea	○	○	●
Pisione remota	○	○	●
Pista cristata	○	○	●
Podarkeopsis capensis	○	○	●
Poecilochaetus serpens	○	○	●
Polycirrus spp.	○	○	●
Polydora ciliata	●	○	○
Polygordius spp.	○	○	●
Polynoe scolopendrina	○	○	●
Praxillella affinis	○	○	●
Procerastea spp.	○	○	●
Protodorvillea kefersteini	○	○	●
Psamathe fusca	○	○	●
Pseudomystides limbata	○	○	●
Pseudopolydora pulchra	○	●	●
Pseudopotamilla reniformis	○	○	●
Sabella pavonina	○	○	●
Sabellaria spinulosa	●	●	●
Saccocirrus papillocercus	○	○	●
Scalibregma spp.	○	○	●
Schistomeringos spp.	○	○	●
Sclerocheilus minutus	○	○	●
Scolelepis spp.	○	○	●
Scoloplos armiger	○	○	●
Sphaerodorum gracilis	○	○	●
Sphaerosyllis spp.	○	○	●
Spio spp.	○	○	●
Spiophanes bombyx	○	○	●
Spirobranchus lamarcki	○	○	●
Spirobranchus triqueter	●	●	●
Spirorbis spirorbis	●	●	○
Sthenelais boa	●	○	●

Streptodonta pterochaeta	○	○	●
Subadyte pellucida	●	○	○
Syllidia armata	○	○	●
Syllis spp.	●	○	●
Terebellides stroemi	○	○	●
Tharyx killariensis	○	○	●
Thelepus spp.	○	○	●
Arthropoda			
Mysida	●	●	●
Copepoda	●	●	●
Decapoda			
Anapagurus chiroacanthus	○	○	●
Atelecyclus spp.	●	○	●
Axius stirhynchus	○	○	●
Callianassidae	○	○	●
Cancer pagurus	●	●	○
Carcininae	●	○	○
Crangon spp.	○	●	●
Ebalia spp.	○	○	●
Eualus cranchii	●	○	●
Eualus occultus	○	○	●
Galathea intermedia	●	○	●
Galathea squamifera	○	●	○
Galathea strigosa	○	●	○
Hippolyte varians	●	○	○
Liocarcinus spp.	●	●	●
Majoidea	●	●	●
Paguridae	●	●	●
Palaemonidae	○	●	○
Pandalina brevirostris	○	○	●
Pandalus tridens	○	●	○
Pilumnus hirtellus	●	○	●
Pilumnus spinifer	●	○	○
Pinnotheres pisum	●	○	●
Pisidia longicornis	●	●	●
Porcellanidae	○	●	○
Portunidae	●	○	○
Thia scutellata	○	○	●
Upogebia deltaura	○	○	●
Hexanauplia			
Cirripedia	●	○	○

Hexapoda			
Telmatogeton japonicus	●	○	○
Isopoda			
Anthura gracilis	○	○	●
Eurydice spinigera	○	○	●
Gnathia oxyuraea	○	○	●
Idotea spp.	●	○	●
Ione thoracica	○	○	●
Janira maculosa	○	○	●
Pleurocrypta spp.	○	○	●
Ostracoda			
Ostracoda	○	○	●
Peracarida			
Abludomelita obtusata	●	○	●
Acidostoma obesum	○	○	●
Ampelisca spp.	○	○	●
Amphilochus manudens	○	○	●
Aora gracilis	●	●	●
Apocorophium lacustre	●	○	○
Apolochus neapolitanus	○	○	●
Apseudes talpa	○	○	●
Bathyporeia spp.	○	○	●
Caprellidae	●	●	○
Cheirocratus spp.	○	○	●
Chelicorophium curvispinum	●	○	○
Cressa dubia	○	○	●
Cumacea	●	○	●
Dyopedos monacanthus	○	○	●
Ericthonius spp.	○	●	●
Gammaridea	●	●	○
Gammaropsis maculata	○	○	●
Gitana sarsi	●	○	○
Harpinia pectinata	○	○	●
Hyperia galba	○	●	○
Iphimedia spp.	○	○	●
Ischyrocerus anguipes	○	●	○
Jassa spp.	●	●	●
Lepidepecreum longicornis	○	●	○
Leptocheirus hirsutimanus	○	○	●
Leucothoe procera	○	○	●
Lysianassidae	●	●	●
Maerella tenuimana	○	○	●

Melitidae	●	○	○
Metopa borealis	●	○	●
Metopa bruzelii	●	○	○
Metopa pusilla	●	○	○
Metopa rubrovittata	○	○	●
Microprotopus maculatus	●	○	○
Monocorophium acherusicum	●	●	○
Monocorophium insidiosum	●	○	○
Monocorophium sextonae	●	○	●
Nototropis swammerdamei	●	○	●
Nototropis vedlomensis	○	○	●
Othomaera othonis	○	○	●
Parametaphoxus tulearensis	○	○	●
Pariambus typicus	○	○	●
Photis spp.	○	○	●
Phtisica marina	●	○	●
Podoceridae	○	○	●
Pseudoprotella phasma	○	○	●
Schistomysis kervillei	○	○	●
Stenothoe marina	●	●	●
Stenothoe monoculoides	●	○	●
Stenothoe tergestina	●	○	○
Stenothoe valida	●	○	○
Stenula solsbergi	●	○	○
Synchelidium intermedium	○	○	●
Tanaopsis graciloides	○	○	●
Tryphosa nana	●	○	●
Tryphosella sarsi	○	●	○
Unciola crenatipalma	○	○	●
Urothoe spp.	○	○	●
Pantopoda			
Achelia echinata	○	○	●
Anoplodactylus petiolatus	○	○	●
Callipallene	○	○	●
Nymphonidae	○	●	●
Sessilia			
Balanus balanus	●	●	○
Balanus crenatus	●	○	●
Balanus improvisus	●	○	○
Balanus perforatus	○	●	○
Perforatus perforatus	●	○	○
Semibalanus balanoides	●	○	○

Verruca stroemia	●	●	●
Brachiopoda			
Gwynia capsula	○	○	●
Bryozoa			
Gymnolaemata			
Aetea anguina	●	○	○
Alcyonidioides mytili	●	○	●
Alcyonidium condylocinereum	●	○	○
Alcyonidium diaphanum	○	●	●
Alcyonidium hydrocoalitum	○	●	○
Alcyonidium parasiticum	●	●	○
Amathia spp.	●	○	●
Amphiblestrum auritum	○	○	●
Arachnidium fibrosum	●	○	○
Aspidelectra melolontha	●	○	●
Bicellariella spp.	●	●	●
Bugulina flabellata	○	●	○
Bugulina turbinata	●	○	○
Buskia nitens	●	○	○
Callopora dumerilii	●	○	●
Cellepora pumicosa	○	○	●
Celleporella hyalina	●	○	○
Chorizopora brongniarti	○	○	●
Conopeum reticulum	●	●	●
Cribrilaria innominata	○	○	●
Cribrilina punctata	●	○	●
Crisularia plumosa	○	●	●
Cryptosula spp.	○	●	○
Electra monostachys	●	○	●
Electra pilosa	●	●	●
Escharella spp.	●	○	●
Escharina johnstoni	○	○	●
Escharoides coccinea	○	●	○
Flustra foliacea	○	●	●
Hagiosynodos latus	○	○	●
Hincksina flustroides	○	○	●
Hippothoa divaricata	○	○	●
Hippothoa flagellum	○	○	●
Membranipora spp.	○	●	○
Microporella ciliata	●	○	●
Nolella spp.	○	○	●
Phylactella labrosa	○	○	●

Porella spp.	○	○	●
Puellina venusta	○	○	●
Reptadeonella violacea	○	○	●
Schizomavella spp.	●	●	●
Schizoporella spp.	○	○	●
Scruparia ambigua	●	●	○
Scruparia chelata	●	○	○
Scrupocellaria spp.	○	●	●
Turbicellepora avicularis	○	○	●
Vesicularia spinosa	○	○	●
Chromista			
Laminaria hyperborea	○	●	○
Laminaria saccharina	○	●	○
Stenolaemata			
Crisia spp.	○	●	●
Disporella hispida	○	○	●
Oncousoecia dilatans	○	○	●
Plagioecia spp.	○	●	●
Tubulipora spp.	○	○	●
Chaetognatha			
Sagitta spp.	○	○	●
Cephalorhyncha			
Priapulida	●	○	○
Chlorophyta			
Chlorophyta	●	○	○
Chordata			
Ascidiacea			
Aplidium turbinatum	○	●	○
Ascidia conchilega	○	○	●
Ascidiella spp.	○	○	●
Clavelina lepadiformis	○	●	○
Dendrodoa grossularia	○	○	●
Didemnidae	○	○	●
Diplosoma listerianum	●	●	○
Molgulidae	●	○	●
Perophora japonica	○	●	○
Polycarpa spp.	○	○	●
Leptocardii			
Branchiostoma lanceolatum	○	○	●
Cnidaria			
Anthozoa			
Alcyonium digitatum	●	●	●

Cerianthus lloydii	○	○	●
Corynactis viridis	●	○	○
Diadumene cincta	●	●	○
Diadumene lineata	●	○	○
Edwardsia spp.	○	○	●
Metridium dianthus	●	●	○
Parazoanthus axinellae	○	○	●
Sagartiidae	●	●	○
Urticina spp.	●	●	○
Hydrozoa			
Abietinaria spp.	○	●	●
Bougainvilliidae	●	●	●
Calycella syringa	●	●	●
Campanularia volubilis	○	●	○
Clytia gracilis	●	○	●
Clytia hemisphaerica	●	●	●
Corymorphidae	●	○	○
Coryne spp.	●	○	●
Diphasia rosacea	○	●	○
Eudendrium spp.	●	●	●
Gonothyraea loveni	●	○	○
Halecium spp.	○	●	●
Hartlaubella gelatinosa	●	○	○
Hydractinia echinata	●	○	●
Hydrallmania falcata	○	●	●
Kirchenpaueria pinnata	○	○	●
Laomedea calceolifera	●	○	○
Laomedea flexuosa	●	○	○
Laomedea neglecta	●	○	○
Nemertesia antennina	○	○	●
Obelia spp.	●	●	●
Phialella quadrata	○	○	●
Plumularia spp.	○	●	●
Sertularella spp.	○	●	●
Tubulariidae	●	●	●
Echinoderm			
Asteroidea	●	●	○
Echinoidea	●	●	●
Ophiuroidea	●	●	●
Holothuriidae	○	○	●
Entoprocta			
Pedicellina spp.	○	●	●

Mollusca			
Bivalvia			
Aequipecten opercularis	●	○	●
Anomia ephippium	●	○	○
Arca tetragona	○	○	●
Barnea spp.	○	○	●
Buccinoidea	●	○	●
Euheterodonta	●	●	●
Glycymeris glycymeris	○	○	●
Goodallia triangularis	○	○	●
Heteranomia squamula	●	○	○
Mimachlamys varia	○	○	●
Modiolus spp.	○	○	●
Musculus discors	○	●	○
Musculus subpictus	●	●	●
Mytilus edulis	●	●	●
Nucula spp.	●	○	●
Ostreidae	●	○	○
Gastropoda			
Acanthodoris pilosa	●	○	○
Adalaria proxima	●	○	○
Aeolidiidae	●	●	○
Brachystomia scalaris	●	○	○
Caecum glabrum	○	○	●
Calliostoma zizyphinum	○	○	●
Catriona gymnota	●	○	○
Coryphella spp.	●	○	○
Crepidula fornicata	○	●	●
Dendronotus frondosus	●	●	●
Diodora graeca	○	○	●
Dorididae	●	○	○
Doto spp.	○	●	●
Embletonia pulchra	○	○	●
Epitonium clathratulum	○	○	●
Epitonium clathrus	●	○	○
Eubranchus spp.	●	○	●
Euspira spp.	●	○	●
Facelina bostoniensis	○	●	○
Flabellinidae	●	●	○
Gibbula spp.	○	●	●
Goniodoris nodosa	○	○	●
Janolus cristatus	○	●	○

Knoutsodonta depressa	○	○	●
Limacia clavigera	○	○	●
Noemiamea dolioliformis	○	○	●
Onchidorididae	●	●	●
Polycera quadrilineata	●	●	○
Pyramidellidae	●	○	●
Rissoa spp.	○	●	○
Sacoglossa	○	○	●
Tergipedidae	●	○	○
Thecacera pennigera	○	○	●
Tornus subcarinatus	○	○	●
Tritia incrassata	○	●	○
Tritia reticulata	○	○	●
Tritonia spp.	●	○	●
Polyplacophora			
Leptochiton asellus	○	○	●
Nematoda			
Nematoda	○	○	●
Nemertea			
Nemertea	●	○	●
Ochrophyta			
Phaeophyceae	●	○	○
Phoronida			
Phoronis spp.	○	○	●
Platyhelminthes			
Platyhelminthes	●	○	●
Porifera			
Aplysina spp.	○	●	○
Biemna variantia	○	●	○
Cliona spp.	○	●	●
Halichondria spp.	●	●	○
Leucosolenia spp.	●	●	○
Myxilla incrustans	○	●	○
Raspailia spp.	○	○	●
Sycon ciliatum	○	●	○
Rhodophyta	●	●	●
Sipuncula			
Golfingia spp.	○	○	●
Nephasoma minutum	○	○	●
Phascolion strombus	○	○	●

Appendix C Biological traits tables (Chapter 4.3.2)

Table C-1 List of taxa and corresponding abbreviations

Taxa name	Abbreviation
Group A	
Corophiidae	Coro
Diadumene spp.	Diad
Diplosoma spp.	Dip
Galathowenia spp.	Galat
Hyperia spp.	Hype
Iphimedia spp.	Iph
Jasmineira spp.	Jsm
Melitidae	Meli
Metopa spp.	Meto
Microporella spp.	Micrel
Mysta spp.	Mys
Photis spp.	Phot
Sabella spp.	Sab
Spirobranchus spp.	Spiro
Group B	
Actinothoe spp.	Acti
Asteroidea	Ast
Balanidae	Ba
Brachystomia spp.	Brac
Caprella spp.	CCa
Corynactis spp.	Coryt
Echinoidea	Echin
Euheterodonta	Euhete
Euspira spp.	Eusp
Haplosyllis spp.	Haplo
Lagotia viridis	Lago
Nephtys spp.	Nephy
Ophiocten spp.	Ophioct
Pinnotheres spp.	Pinn
Polynoe scolopendrina	Polyne
Saccocirrus spp.	Sacc
Verruca spp.	Verr
Group C	
Aeolidiidae	Aeoli
Alcyonidium spp.	Alcyo
Alcyonium spp.	Alcym
Ampelisca spp.	Ampe
Ampharete spp.	Amphar
Amphipholis spp.	Amphip

Anomiidae	Anom
Aonides spp.	Aoni
Aoridae	Aorid
Bathyporeia spp.	Bath
Campanulariidae	Campa
Cancer spp.	Canc
Caulleriella spp.	Caul
Clytia spp.	Clyti
Copepoda	Cop
Dendrodoa spp.	Dend
Electra spp.	Elect
Eteoninae	Eteo
Eubranchus spp.	Eubr
Eudendrium spp.	Euden
Eulalia spp.	Eula
Eumida spp.	Eumid
Flabelligera spp.	Flab
Gibbula spp.	Gibb
Gitana spp.	Gita
Glycera spp.	Glyce
Hesionura spp.	Hesi
Heteranomia spp.	Heten
Kirchenpaueria pinnata	Kirc
Lepidepecreum spp.	Lepidepecre
Liparis spp.	Lipa
Lumbrineridae	Lumb
Marphysa spp.	Marp
Mediomastus spp.	Medi
Myrianida spp.	Myria
Mytilidae	Myti
Nemertea	Neme
Nephasoma spp.	Nepha
Nothria spp.	Noth
Notomastus spp.	Notom
Nymphonidae	Nymph
Oligochaeta	Oligo
Oncousoecia dilatans	Onco
Ophiuroidea	Ophi
Pandalina spp.	Panda
Phoronis spp.	Phor
Pisidia spp.	Pisid
Polycarpa spp.	Polyca
Polycirrus spp.	Polyci
Priapulida	Pria
Psamathe spp.	Psamt

Pygospio spp.	Pygo
Sabellaria spp.	Saber
Sagitta spp.	Sagi
Scalibregma spp.	Scal
Semibalanus spp.	Semi
Spiophanes spp.	Spiop
Syllidia spp.	Sylld
Tanaopsis spp.	Tanap
Telmatogeton spp.	Telm
Terebellida	Tere
Tubulariidae	Tubul
Urothoe spp.	Urot
Urticina spp.	Urti
Group D	
Abietinaria spp.	Abie
Abludomelita spp.	Ablu
Acanthodoris spp.	Acan
Achelia spp.	Ache
Acidostoma spp.	Acid
Adalaria spp.	Adal
Aequipecten spp.	Aequ
Aetea spp.	Aete
Alcyonidioides spp.	Alcyd
Amaeana spp.	Amae
Amathia spp.	Amat
Amphiblestrum spp.	Amphib
Amphicteis spp.	Amphic
Amphilochus spp.	Amphil
Amphiura spp.	Amphur
Anapagurus spp.	Anap
Anoplodactylus spp.	Anop
Anthura spp.	Anth
Aphelochaeta spp.	Aphe
Aphrodita spp.	Aphr
Aplysina spp.	Aply
Apseudes spp.	Apse
Arachnidium spp.	Arac
Arca spp.	Arca
Aricidea spp.	Aric
Ascidia spp.	Asc
Ascidiella spp.	Asdil
Asclerocheilus spp.	Ascl
Aspidelectra spp.	Aspi
Astarte spp.	Asta
Atelecyclus spp.	Atel

Atherospio spp.	Athe
Axius stirhynchus	Axiu
Barnea spp.	Barn
Bicellariella spp.	Bice
Bougainvilliidae	Boug
Branchiostoma spp.	Bran
Buccinoidea	Bucc
Buskia spp.	Busk
Caecum spp.	Caec
Callianassa spp.	Calla
Calliostoma spp.	Calli
Callipallene	Callp
Callopora spp.	Callo
Calycella spp.	Calyc
Capitellidae	Capit
Carcininae	Carc
Cellepora spp.	Cell
Celleporella spp.	Cellrel
Cerastoderma edule	Cera
Cerianthus spp.	Ceri
Chaetopterus spp.	Chaep
Chaetozone spp.	Chaez
Cheirocratus spp.	Chei
Chorizopora spp.	Chor
Cirratulidae	Cirr
Cliona spp.	Clio
Clymenura spp.	Clym
Conopeum spp.	Conop
Coryne spp.	Corye
Crangon spp.	Crang
Crepidula spp.	Crepi
Cressa spp.	Cres
Cribrilina spp.	Crib
Crisia spp.	Crisa
Crisularia plumosa	Crisu
Ctenolabrus spp.	Cten
Cumacea	Cuma
Dendronotus spp.	Dendr
Didemnidae	Dide
Diodora graeca	Diod
Disporella spp.	Disp
Dorididae	Dori
Doto spp.	Doto
Drilonereis spp.	Dril
Dyopedos spp.	Dyop

Ebalia spp.	Ebal
Echiuridae	Echiu
Ectopleura spp.	Ectop
Edwardsia spp.	Edwa
Embletonia spp.	Embl
Ephesiella spp.	Ephe
Epitonium spp.	Epit
Ericthonius spp.	Erict
Escharella spp.	Eschl
Escharina spp.	Eschn
Eualus spp.	Eual
Euclymene spp.	Eucl
Eunereis spp.	Eune
Eupolymnia spp.	Eupo
Eurydice spp.	Eury
Eusyllinae	Eusy
Exogone spp.	Exog
Fabulina spp.	Fabu
Facelina spp.	Facel
Filifera	Fili
Filograna implexa	Filo
Galatheoidea	Gala
Gammaridea	Gammd
Gammaropsis spp.	Gammp
Gattyana spp.	Gatt
Glycinde spp.	Glyci
Glycymeris spp.	Glycy
Gnathia spp.	Gnath
Golfingia spp.	Golf
Goniada spp.	Gonia
Goniodoris nodosa	Gonir
Goodallia spp.	Good
Gwynia capsula	Gwyn
Gyptis spp.	Gypt
Hagiosynodos latus	Hagi
Halecium spp.	Hale
Harmothoe spp.	Harm
Harpinia spp.	Harp
Hartlaubella spp.	Hart
Heterobranchia	Heteb
Hincksina flustroides	Hinc
Hippolyte spp.	Hippy
Hippothoa spp.	Hippa
Holothuriidae	Holo
Hyas spp.	Hyas

Hydractinia spp.	Hydr
Hydrallmania spp.	Hydra
Idotea spp.	Idot
Ione spp.	Ione
Ischyroceridae	Ischy
Isopoda	Isop
Janua spp.	Janu
Jassa spp.	Jass
Kellia spp.	Kell
Kurtiella spp.	Kurt
Lagis spp.	Lagi
Lanice spp.	Lani
Laomedea spp.	Laom
Laonice spp.	Laoni
Lepidonotus spp.	Lepi
Leptocheirus spp.	Leptr
Leptochiton spp.	Leptt
Leucosolenia spp.	Leucs
Leucothoe spp.	Leuct
Limacia spp.	Limac
Liocarcinus spp.	Lioca
Lysianassidae	Lysin
Lysidice spp.	Lysid
Macrochaeta spp.	Macro
Macropodia spp.	Macr
Maerella spp.	Maer
Magelona spp.	Mage
Majoidea	Majo
Maldanidae	Mald
Malmgrenia spp.	Malm
Metridium spp.	Metr
Micromaldane ornithochaeta	Microm
Microphthalmus spp.	Micrth
Microprotopus spp.	Microt
Microspio spp.	Micros
Mimachlamys varia	Mima
Molgulidae	Molg
Mya spp.	Mya
Mysida	Mysi
Neoamphitrite spp.	Neoa
Neogastropoda	Neog
Nereididae	Nered
Nereis spp.	Neres
Nicolea spp.	Nicol
Nicomache spp.	Nicom

Noemiamea dolioliformis	Noem
Nolella spp.	Nole
Nototropis spp.	Notot
Nuculidae	Nucu
Obelia spp.	Obel
Odontosyllis spp.	Odon
Onchidorididae	Onch
Ophelia spp.	Ophe
Ostracoda	Ostra
Ostreidae	Ostre
Othomaera othonis	Otho
Owenia spp.	Owen
Oxydromus spp.	Oxyd
Paguridae	Pagur
Palaemonidae	Palae
Pandalidae	Pand
Pantopoda	Pant
Paradoneis spp.	Parad
Parametaphoxus spp.	Param
Paranaitis spp.	Paran
Pariambus spp.	Pari
Pectinidae	Pecti
Pedicellina spp.	Pedi
Perforatus spp.	Perf
Perkinsiana rubra	Perk
Petaloproctus spp.	Peta
Phaeophyceae	Phae
Phascolion spp.	Phas
Pherusa spp.	Pher
Phialella spp.	Phia
Pholis spp.	Pholi
Pholoe spp.	Pholo
Phtisica spp.	Phti
Phylactella labrosa	Phyla
Phyllodoce spp.	Phyld
Pilumnus spp.	Pilu
Pisione spp.	Pisin
Pista spp.	Pist
Plagioecia spp.	Plag
Platyhelminthes	Plat
Pleurocrypta spp.	Pleuc
Pleuronectes spp.	Pleun
Plumularia spp.	Plum
Podarkeopsis spp.	Poda
Podoceridae	Podo

Poecilochaetus spp.	Poec
Polycera spp.	Polyce
Polydora spp.	Polyd
Polygordius spp.	Polyg
Polynoidae	Polynd
Porcellanidae	Porc
Porella spp.	Pore
Portunidae	Port
Praxillella spp.	Prax
Proceraea spp.	Proce
Procerastea spp.	Procs
Prosobranchia	Pros
Protodorvillea spp.	Prot
Psammechinus spp.	Psamc
Pseudomystides spp.	Pseud
Pseudopolydora spp.	Pseul
Pseudopotamilla spp.	Pseut
Pseudoprotella spp.	Pseur
Puellina spp.	Puel
Pyramidellidae	Pyra
Raspailia spp.	Rasp
Reptadeonella violacea	Rept
Rissoa spp.	Riss
Sabellidae	Sabed
Sagartiidae	Saga
Schistomeringos spp.	Schig
Schistomysis spp.	Schis
Schizomavella spp.	Schiv
Schizoporella spp.	Schip
Sclerocheilus minutus	Scle
Scolelepis spp.	Scol
Scoloplos spp.	Scolo
Scruparia spp.	Scrua
Scrupocellaria spp.	Scruo
Serpulidae	Serp
Sphaerodoropsis baltica	Sphap
Sphaerodorum spp.	Spham
Sphaerosyllis spp.	Sphas
Spio spp.	Spio
Stenothoe spp.	Steno
Stenula spp.	Stenu
Sthenelais spp.	Sthe
Streptodonta pterochaeta	Stre
Subadyte spp.	Subad
Sycon spp.	Syco

Syllis spp.	Sylls
Synchelidium spp.	Sync
Tanaissus lilljeborgi	Tanas
Tergipedidae	Terg
Tharyx spp.	Thar
Thecacera pennigera	Thec
Thelepus spp.	Thel
Thia spp.	Thia
Tornus spp.	Torn
Travisia spp.	Trav
Tritonia spp.	Trit
Tryphosa spp.	Tryp
Tryphosella spp.	Tryph
Tubulipora spp.	Tubu
Turbicellepora spp.	Turb
Unciola spp.	Unci
Upogebia spp.	Upog
Vesicularia spp.	Vesi

Table C-2 Bioturbation traits table

Taxa	bDiff	bDown	bEpi	bReg	bSurf	bUp
Abie	0	0	3	0	0	0
Ablu	0	0	0	1	2	1
Acan	3	0	0	0	0	0
Ache	0	0	3	0	0	0
Acid	1	0	1	0	2	0
Acti	0	0	3	0	0	0
Adal	1	0	2	0	1	0
Aeoli	0	0	0	0	1	0
Aequ	0	0	3	0	0	0
Aete	0	0	3	0	0	0
Alcyd	1	0	2	0	1	0
Alcym	0	0	3	0	0	0
Alcyo	0	0	3	0	0	0
Amae	0	0	0	0	1	0
Amat	0	0	3	0	0	0
Ampe	2	0	1	0	2	2
Amphar	0	0	0	0	3	0
Amphib	0	0	3	0	0	0
Amphic	0	0	0	0	1	0
Amphil	0	0	1	0	1	0
Amphip	0	0	3	0	0	0
Amphur	3	0	0	0	3	0
Anap	1	0	3	0	2	0
Anom	0	0	3	0	0	0
Anop	0	0	3	0	0	0
Anth	0	0	3	0	0	0
Aoni	2	2	3	0	0	0
Aorid	2	0	3	0	3	2
Aphe	0	2	0	0	3	0
Aphr	3	0	0	0	3	0
Aply	1	0	2	0	1	0
Apse	3	0	3	0	2	0
Arac	1	0	2	0	1	0
Arca	0	0	3	0	0	0
Aric	3	0	0	0	3	0
Asc	0	0	3	0	0	0
Ascl	3	0	0	0	0	0
Asdil	0	0	3	0	0	0
Aspi	0	0	3	0	0	0
Ast	0	0	0	0	1	0
Asta	0	0	0	0	1	0
Atel	2	0	0	3	3	0

Athe	0	2	2	0	1	0
Axiu	0	0	0	0	0	0
Ba	0	0	3	0	1	0
Barn	0	0	0	0	0	0
Bath	3	0	0	0	3	0
Bice	0	0	3	0	0	0
Boug	0	0	3	0	0	0
Brac	0	0	3	0	0	0
Bran	1	0	0	0	3	0
Bucc	2	0	0	0	2	0
Busk	1	0	2	0	1	0
Caec	1	0	0	0	3	0
Calla	3	0	0	0	0	0
Calli	0	0	3	0	2	0
Callo	0	0	3	0	0	0
Callp	0	0	3	0	0	0
Calyc	0	0	3	0	0	0
Campa	0	0	3	0	0	0
Canc	1	0	0	0	3	0
Capit	3	0	0	0	0	2
Carc	0	0	2	0	0	0
Caul	0	2	0	0	3	0
CCa	0	0	3	0	0	0
Cell	0	0	3	0	0	0
Cellrel	0	0	3	0	0	0
Cera	0	1	0	0	0	2
Ceri	0	0	0	0	2	0
Chaep	1	0	0	0	3	0
Chaez	0	2	0	0	3	0
Chei	0	0	0	3	3	1
Chor	0	0	3	0	0	0
Cirr	1	2	0	0	2	0
Clio	0	0	3	0	0	0
Clym	0	0	0	0	0	3
Clyti	0	0	3	0	0	0
Conop	0	0	3	0	0	0
Cop	0	0	0	0	1	0
Coro	2	0	1	1	1	1
Corye	0	0	3	0	0	0
Coryt	0	0	3	0	2	0
Crang	1	0	2	0	2	0
Crepi	0	0	3	0	0	0
Cres	1	0	3	0	1	0
Crib	1	0	2	0	1	0
Crisa	0	0	3	0	0	0

Crisu	0	0	0	0	0	0
Cten	1	0	2	0	1	0
Cuma	1	0	2	0	1	0
Dend	0	0	3	0	0	0
Dendr	0	0	0	0	3	0
Diad	1	0	2	0	1	0
Dide	0	0	3	0	0	0
Diod	0	0	0	0	0	0
Dip	1	0	2	0	1	0
Disp	0	0	3	0	0	0
Dori	0	0	3	1	0	0
Doto	0	0	0	0	3	0
Dril	3	0	0	0	0	0
Dyop	2	0	3	0	0	2
Ebal	0	0	3	0	0	0
Echin	1	0	0	0	1	0
Echiu	0	0	0	0	1	0
Ectop	0	0	3	0	0	0
Edwa	0	0	0	0	3	0
Elect	0	0	3	0	0	0
Embl	0	0	0	0	3	0
Ephe	0	0	1	0	2	0
Epit	0	0	0	0	2	0
Erict	2	0	2	0	2	3
Eschl	0	0	3	0	0	0
Eschn	0	0	3	0	0	0
Eteo	2	0	2	0	0	0
Eual	1	0	2	0	2	0
Eubr	0	0	3	0	0	0
Eucl	0	0	0	0	0	3
Euden	0	0	3	0	0	0
Euhete	0	0	1	0	2	0
Eula	2	0	2	0	0	0
Eumid	2	0	2	0	0	0
Eune	2	1	2	0	0	0
Eupo	0	0	0	0	3	0
Eury	1	0	0	0	3	0
Eusp	3	0	1	0	0	0
Eusy	1	0	2	0	1	0
Exog	1	0	2	0	1	0
Fabu	0	0	1	0	1	1
Facel	0	0	3	0	0	0
Fili	0	0	3	0	0	0
Filo	0	0	0	0	0	0
Flab	0	0	1	0	3	0

Gala	0	0	3	0	0	0
Galat	0	3	0	0	0	0
Gammd	1	0	2	0	1	0
Gammp	2	0	1	0	2	1
Gatt	2	0	1	0	0	0
Gibb	0	0	3	0	0	0
Gita	2	2	0	0	0	2
Glyce	3	0	0	0	0	0
Glyci	3	0	0	0	0	0
Glycy	0	0	3	0	0	0
Gnath	0	0	1	0	0	0
Golf	1	0	0	0	3	0
Gonia	3	0	0	0	0	0
Gonir	0	0	0	0	0	0
Good	2	0	0	0	1	0
Gwyn	0	0	0	0	0	0
Gypt	2	0	0	0	2	0
Hagi	0	0	0	0	0	0
Hale	0	0	3	0	0	0
Haplo	1	0	2	0	1	0
Harm	2	0	1	0	0	0
Harp	3	0	0	0	3	0
Hart	1	0	2	0	1	0
Hesi	2	0	2	0	0	0
Heteb	1	0	2	0	1	0
Heten	0	0	3	0	0	0
Hinc	0	0	0	0	0	0
Hippa	0	0	3	0	0	0
Hippy	1	0	2	0	2	0
Holo	0	0	0	0	0	0
Hyas	0	0	3	0	0	0
Hydr	1	0	2	0	1	0
Hydra	0	0	3	0	0	0
Hype	1	0	2	0	1	0
Idot	1	0	3	0	1	0
Ione	0	0	0	0	0	0
Iph	1	0	3	0	1	0
Ischy	2	0	2	0	2	2
Isop	1	0	2	0	1	0
Janu	0	0	0	0	0	0
Jass	3	0	3	0	2	0
Jsm	0	0	0	0	3	0
Kell	0	0	3	0	0	0
Kirc	0	0	0	0	0	0
Kurt	2	0	0	0	1	0

Lagi	0	0	0	0	0	3
Lago	0	0	0	0	0	0
Lani	1	0	0	0	3	0
Laom	0	0	3	0	0	0
Laoni	0	2	2	0	3	0
Lepi	2	0	1	0	0	0
Lepidepecre	1	0	1	0	2	0
Leptr	2	0	3	0	1	3
Leptt	0	0	3	0	0	0
Leucs	0	0	3	0	0	0
Leuct	1	0	2	0	2	0
Limac	0	0	0	0	1	0
Lioca	1	0	2	0	2	0
Lipa	1	0	2	0	1	0
Lumb	2	0	0	0	0	0
Lysid	0	2	3	0	0	0
Lysin	1	0	1	0	2	0
Macr	0	0	3	0	0	0
Macro	0	0	3	0	1	0
Maer	1	0	0	3	2	3
Mage	1	3	0	0	1	0
Majo	0	0	3	0	0	0
Mald	0	0	0	0	0	3
Malm	2	0	1	0	0	0
Marp	0	2	3	0	0	0
Medi	3	0	0	0	0	3
Meli	0	0	0	1	2	1
Meto	1	0	1	0	2	0
Metr	0	0	3	0	0	0
Micrel	0	0	3	0	0	0
Microm	0	0	0	0	0	0
Micros	0	2	2	0	1	0
Microt	0	0	1	2	3	2
Micrth	2	0	0	0	2	0
Mima	0	0	0	0	0	0
Molg	0	0	0	0	3	0
Mya	2	0	0	0	3	0
Myria	1	0	2	0	3	0
Mys	2	0	2	0	0	0
Mysi	1	0	2	0	1	0
Myti	0	0	3	0	1	0
Neme	1	0	0	0	1	0
Neoa	0	1	0	0	1	0
Neog	1	0	2	0	1	0
Nepha	1	0	3	0	3	0

Nephy	3	0	0	0	0	0
Nered	2	1	2	0	0	0
Neres	2	1	2	0	0	0
Nicol	0	0	0	0	1	0
Nicom	0	0	0	0	0	3
Noem	0	0	0	0	0	0
Nole	0	0	3	0	0	0
Noth	2	2	0	0	1	0
Notom	3	0	0	0	0	2
Notot	1	0	2	0	1	0
Nucu	2	0	0	0	0	0
Nymph	0	0	3	0	0	0
Obel	0	0	3	0	0	0
Odon	1	0	2	0	1	0
Oligo	2	0	0	0	2	0
Onch	0	0	0	0	1	0
Onco	0	0	0	0	0	0
Ophe	3	0	0	0	0	0
Ophi	0	0	0	0	1	0
Ophioct	3	0	0	0	3	0
Ostra	0	0	0	0	1	0
Ostre	0	0	3	0	0	0
Otho	0	0	0	0	0	0
Owen	0	3	0	0	0	0
Oxyd	3	0	0	0	2	0
Pagur	1	0	3	0	2	0
Palae	1	0	2	0	1	0
Pand	1	0	2	0	1	0
Panda	1	0	2	0	2	0
Pant	1	0	2	0	1	0
Parad	3	0	0	0	3	0
Param	3	0	0	0	3	0
Paran	2	0	2	0	0	0
Pari	1	0	3	0	0	1
Pecti	0	0	3	0	0	0
Pedi	0	0	1	0	0	0
Perf	0	0	3	0	0	0
Perk	0	0	0	0	0	0
Peta	0	0	0	0	0	3
Phae	1	0	2	0	1	0
Phas	1	0	0	0	3	0
Pher	0	0	1	0	3	0
Phia	0	0	3	0	0	0
Pholi	1	0	2	0	1	0
Pholo	3	0	3	0	0	0

Phor	0	0	3	0	0	0
Phot	2	0	1	0	2	1
Phti	0	0	3	0	0	1
Phyla	0	0	0	0	0	0
Phyld	2	0	2	0	0	0
Pilu	0	0	3	0	0	0
Pinn	0	0	3	0	0	0
Pisid	0	0	3	0	0	0
Pisin	3	0	0	0	0	0
Pist	0	0	0	0	3	0
Plag	0	0	3	0	0	0
Plat	0	0	0	0	1	0
Pleuc	0	0	0	0	0	0
Pleun	1	0	2	0	1	0
Plum	0	0	3	0	0	0
Poda	1	0	0	0	3	0
Podo	1	0	2	0	0	0
Poec	1	0	0	0	3	0
Polyca	0	0	3	0	0	0
Polyce	0	0	3	0	0	0
Polyci	0	0	0	0	3	0
Polyd	0	2	2	0	1	0
Polyg	1	0	0	0	0	0
Polynd	2	0	1	0	0	0
Polyne	0	0	0	0	0	0
Porc	1	0	2	0	1	0
Pore	0	0	3	0	0	0
Port	1	0	2	0	1	0
Prax	0	0	0	0	0	3
Pria	0	3	0	0	0	0
Proce	1	0	2	0	1	0
Procs	0	0	0	0	0	0
Pros	1	0	2	0	1	0
Prot	3	0	2	0	2	0
Psamc	0	0	0	0	3	0
Psamt	2	0	0	0	2	0
Pseud	2	0	2	0	0	0
Pseul	0	2	2	0	3	0
Pseur	0	0	3	0	0	1
Pseut	0	0	0	0	1	0
Puel	0	0	3	0	0	0
Pygo	0	2	2	0	1	0
Pyra	3	0	3	0	0	0
Rasp	0	0	0	0	0	0
Rept	0	0	0	0	0	0

Riss	1	0	1	0	3	0
Sab	0	0	0	0	1	0
Sabed	0	0	0	0	1	0
Saber	0	0	0	0	3	0
Sacc	1	0	0	0	0	0
Saga	0	0	3	0	0	0
Sagi	0	0	0	0	0	0
Scal	3	0	0	0	0	0
Schig	1	0	2	0	2	0
Schip	0	0	3	0	0	0
Schis	0	0	0	0	1	0
Schiv	0	0	3	0	0	0
Scle	0	0	0	0	0	0
Scol	0	2	2	0	3	0
Scolo	0	2	0	0	0	2
Scrua	0	0	3	0	0	0
Scruo	0	0	3	0	0	0
Semi	0	0	3	0	0	0
Serp	0	0	3	0	0	0
Spham	0	0	1	0	2	0
Sphap	0	0	0	0	0	0
Sphas	1	0	2	0	1	0
Spio	0	2	2	0	3	0
Spiop	0	2	2	0	3	0
Spiro	0	0	3	0	0	0
Steno	1	0	1	0	2	0
Stenu	1	0	1	0	2	0
Sthe	3	0	0	0	1	0
Stre	0	0	0	0	0	0
Subad	2	0	1	0	0	0
Syco	1	0	2	0	1	0
Sylld	2	0	0	0	2	0
Sylls	1	0	2	0	1	0
Sync	3	0	0	0	3	0
Tanap	2	1	0	0	1	0
Tanas	0	0	0	0	0	0
Telm	1	0	2	0	1	0
Tere	1	1	0	0	3	1
Terg	1	0	2	0	1	0
Thar	0	2	0	0	3	0
Thec	0	0	0	0	0	0
Thel	0	0	0	0	1	0
Thia	2	0	0	0	3	0
Torn	0	0	1	0	3	0
Trav	1	0	0	0	0	0

Trit	1	0	2	0	1	0
Tryp	0	0	1	0	0	0
Tryph	1	0	1	0	2	0
Tubu	0	0	3	0	0	0
Tubul	0	0	3	0	0	0
Turb	0	0	3	0	0	0
Unci	2	0	1	0	3	2
Upog	3	0	0	0	0	0
Urot	3	0	0	0	3	0
Urti	0	0	3	0	0	0
Verr	0	0	3	0	1	0
Vesi	0	0	3	0	0	0

Table C-3 Body shape traits table

Taxa	Crustose	Cushion/tunic	Exoskeleton	Soft	Stalked
Abie	0	0	0	3	3
Ablu	0	0	3	0	0
Acan	0	0	0	3	0
Ache	0	0	3	0	0
Acid	0	0	3	0	0
Acti	0	2	0	3	0
Adal	0	0	0	3	0
Aeoli	0	0	0	3	0
Aequ	0	1	3	0	0
Aete	1	0	3	1	1
Alcyd	3	0	0	0	0
Alcym	0	0	0	0	3
Alcyo	3	0	0	3	1
Amae	0	0	0	3	0
Amat	1	0	0	3	2
Ampe	0	0	3	0	0
Amphar	0	0	0	3	0
Amphib	3	0	3	0	0
Amphic	0	0	0	3	0
Amphil	0	0	3	0	0
Amphip	0	0	3	0	1
Amphur	0	0	3	0	1
Anap	0	2	3	0	1
Anom	0	1	3	0	0
Anop	0	0	3	0	0
Anth	0	0	3	0	0
Aoni	0	0	0	3	0
Aorid	0	0	3	0	0
Aphe	0	0	0	3	0
Aphr	0	0	0	3	0
Aply	1	0	0	1	1
Apse	0	0	3	0	0
Arac	1	0	0	0	0
Arca	0	1	3	0	0
Aric	0	0	0	3	0
Asc	2	3	0	2	0
Ascl	0	0	0	3	0
Asdil	0	3	0	2	0
Aspi	1	0	3	0	0
Ast	0	0	3	0	0
Asta	0	0	3	0	0
Atel	0	3	3	0	0

Athe	0	0	0	3	0
Axiu	0	0	3	0	0
Ba	0	0	3	0	0
Barn	0	3	0	0	0
Bath	0	0	3	0	0
Bice	0	3	3	0	3
Boug	0	1	0	3	3
Brac	0	2	3	0	2
Bran	0	1	0	3	3
Bucc	0	0	3	0	3
Busk	3	0	0	0	1
Caec	0	0	3	0	2
Calla	0	0	3	0	1
Calli	0	0	3	0	2
Callo	3	0	3	0	0
Callp	0	0	3	0	0
Calyc	0	1	0	3	3
Campa	0	1	0	3	3
Canc	0	3	3	0	0
Capit	0	0	0	3	0
Carc	0	0	3	0	0
Caul	0	0	0	3	0
CCa	0	0	3	0	0
Cell	0	3	3	0	1
Cellrel	3	0	3	0	0
Cera	0	3	0	0	0
Ceri	0	0	0	3	0
Chaep	0	0	0	3	0
Chaez	0	0	0	3	0
Chei	0	0	3	0	0
Chor	3	0	3	0	0
Cirr	0	0	0	3	0
Clio	0	3	0	0	0
Clym	0	0	0	3	0
Clyti	0	1	0	3	3
Conop	3	0	3	0	0
Cop	0	0	3	0	0
Coro	0	0	3	0	0
Corye	0	1	0	3	3
Coryt	0	3	0	2	0
Crang	0	0	3	0	1
Crepi	3	1	3	0	0
Cres	0	0	3	0	0
Crib	3	0	0	0	0
Crisa	1	3	3	1	0

Crisu	0	0	0	0	3
Cten	0	0	0	1	0
Cuma	0	0	3	0	0
Dend	0	3	0	0	0
Dendr	0	0	0	3	0
Diad	0	0	0	1	2
Dide	0	3	0	2	0
Diod	0	3	0	0	0
Dip	2	0	0	1	0
Disp	3	0	3	1	0
Dori	0	0	0	3	0
Doto	0	0	0	3	0
Dril	0	0	0	3	0
Dyop	0	0	3	0	0
Ebal	0	3	3	0	0
Echin	0	0	3	0	0
Echiu	0	0	0	3	0
Ectop	0	3	0	3	3
Edwa	0	0	0	3	0
Elect	3	0	3	0	0
Embl	0	0	0	3	0
Ephe	0	0	0	3	0
Epit	0	0	3	0	3
Erict	0	0	3	0	0
Eschl	3	0	3	0	0
Eschn	3	0	3	0	0
Eteo	0	0	0	3	0
Eual	0	0	3	0	1
Eubr	0	0	0	3	0
Eucl	0	0	0	3	0
Euden	0	3	0	3	3
Euhete	0	3	0	0	0
Eula	0	0	0	3	0
Eumid	0	0	0	3	0
Eune	0	0	0	3	0
Eupo	0	0	0	3	0
Eury	0	0	3	0	0
Eusp	0	2	3	0	1
Eusy	0	0	0	3	0
Exog	0	0	0	3	0
Fabu	0	0	3	0	0
Facel	0	0	0	3	0
Fili	0	0	0	2	2
Filo	1	2	0	0	0
Flab	0	0	0	3	0

Gala	0	2	3	0	0
Galat	0	0	0	3	0
Gammd	0	0	3	0	0
Gammp	0	0	3	0	0
Gatt	0	0	0	3	0
Gibb	0	3	3	0	0
Gita	0	0	3	0	0
Glyce	0	0	0	3	0
Glyci	0	0	0	3	0
Glycy	0	1	3	0	0
Gnath	0	0	3	0	0
Golf	0	0	0	3	0
Gonia	0	0	0	3	0
Gonir	0	0	0	3	0
Good	0	1	3	0	0
Gwyn	0	3	0	0	0
Gypt	0	0	0	3	0
Hagi	0	0	0	0	0
Hale	0	0	0	3	3
Haplo	0	0	0	3	0
Harm	0	0	0	3	0
Harp	0	0	3	0	0
Hart	0	0	0	1	3
Hesi	0	0	0	3	0
Heteb	0	0	0	3	0
Heten	0	1	3	0	0
Hinc	3	0	0	0	0
Hippa	2	0	3	0	0
Hippy	0	0	3	0	1
Holo	0	0	0	3	0
Hyas	0	2	3	0	2
Hydr	0	0	0	1	3
Hydra	0	3	0	3	3
Hype	0	0	3	0	0
Idot	0	0	3	0	0
Ione	0	0	3	0	0
Iph	0	0	3	0	0
Ischy	0	0	3	0	0
Isop	0	0	3	0	0
Janu	0	3	0	0	0
Jass	0	0	3	0	0
Jsm	0	0	0	3	0
Kell	0	1	3	0	0
Kirc	0	0	0	1	2
Kurt	0	1	3	0	0

Lagi	0	0	0	3	0
Lago	0	0	0	0	0
Lani	0	0	0	3	0
Laom	0	2	0	3	3
Laoni	0	0	0	3	0
Lepi	0	0	0	3	0
Lepidepecre	0	0	3	0	0
Leptr	0	0	3	0	0
Leptt	0	0	3	0	0
Leucs	0	3	0	0	3
Leuct	0	0	3	0	0
Limac	0	0	0	3	0
Lioca	0	3	3	0	1
Lipa	0	0	0	1	0
Lumb	0	0	0	3	0
Lysid	0	0	0	3	0
Lysin	0	0	3	0	0
Macr	0	1	3	0	2
Macro	0	0	0	3	0
Maer	0	0	3	0	0
Mage	0	0	0	3	0
Majo	0	2	3	0	2
Mald	0	0	0	3	0
Malm	0	0	0	3	0
Marp	0	0	0	3	0
Medi	0	0	0	3	0
Meli	0	0	3	0	0
Meto	0	0	3	0	0
Metr	0	2	0	3	0
Micrel	3	0	3	0	0
Microm	0	0	0	0	0
Micros	0	0	0	3	0
Microt	0	0	3	0	0
Micrth	0	0	0	3	0
Mima	0	3	0	0	0
Molg	0	3	0	2	0
Mya	0	0	3	0	1
Myria	0	0	0	3	0
Mys	0	0	0	3	0
Mysi	0	0	3	0	0
Myti	1	0	3	0	0
Neme	0	0	0	3	0
Neoa	0	0	0	3	0
Neog	0	3	0	0	0
Nepha	0	0	0	3	0

Nephy	0	0	0	3	0
Nered	0	0	0	3	0
Neres	0	0	0	3	0
Nicol	0	0	0	3	0
Nicom	0	0	0	3	0
Noem	0	0	0	0	0
Nole	3	0	0	3	1
Noth	0	0	0	3	0
Notom	0	0	0	3	0
Notot	0	0	3	0	0
Nucu	0	3	3	0	0
Nymph	0	0	3	0	0
Obel	0	3	0	3	3
Odon	0	0	0	3	0
Oligo	0	0	0	0	0
Onch	0	0	0	3	0
Onco	3	0	0	0	0
Ophe	0	0	0	3	0
Ophi	0	0	3	0	1
Ophioct	0	0	3	0	1
Ostra	0	0	3	0	0
Ostre	2	3	3	0	0
Otho	0	0	0	0	0
Owen	0	0	0	3	0
Oxyd	0	0	0	3	0
Pagur	0	2	3	0	1
Palae	0	0	3	0	0
Pand	0	0	3	0	0
Panda	0	0	3	0	1
Pant	0	0	3	0	0
Parad	0	0	0	3	0
Param	0	0	3	0	0
Paran	0	0	0	3	0
Pari	0	0	3	0	0
Pecti	0	1	3	0	0
Pedi	0	0	0	0	3
Perf	0	0	3	0	0
Perk	0	2	0	1	0
Peta	0	0	0	3	0
Phae	0	0	0	0	3
Phas	0	0	0	3	0
Pher	0	0	0	3	0
Phia	0	1	0	3	3
Pholi	0	0	0	1	0
Pholo	0	0	0	3	0

Phor	0	0	0	3	0
Phot	0	0	3	0	0
Phti	0	0	3	0	0
Phyla	0	0	0	0	0
Phyld	0	0	0	3	0
Pilu	0	3	3	0	0
Pinn	0	3	3	0	0
Pisid	0	3	3	0	0
Pisin	0	0	0	3	0
Pist	0	0	0	3	0
Plag	3	0	3	1	0
Plat	0	0	0	3	0
Pleuc	0	0	3	0	0
Pleun	0	0	0	1	0
Plum	0	0	0	3	3
Poda	0	0	0	3	0
Podo	0	0	3	0	0
Poec	0	0	0	3	0
Polyca	0	3	0	1	0
Polyce	0	0	0	3	0
Polyci	0	0	0	3	0
Polyd	0	0	0	3	0
Polyg	0	0	0	3	0
Polynd	0	0	0	3	0
Polyne	0	0	0	0	0
Porc	0	0	3	0	0
Pore	1	0	3	0	3
Port	0	0	3	0	0
Prax	0	0	0	3	0
Pria	0	0	0	3	0
Proce	0	0	0	3	0
Procs	0	3	0	0	0
Pros	0	3	0	0	0
Prot	0	0	0	3	0
Psamc	0	2	3	0	0
Psamt	0	0	0	3	0
Pseud	0	0	0	3	0
Pseul	0	0	0	3	0
Pseur	0	0	3	0	0
Pseut	0	0	0	3	0
Puel	3	0	3	0	3
Pygo	0	0	0	3	0
Pyra	0	3	0	0	0
Rasp	0	0	0	1	3
Rept	0	0	0	0	0

Riss	0	2	3	0	1
Sab	0	0	0	3	0
Sabed	0	0	0	3	0
Saber	0	0	0	3	0
Sacc	0	0	0	3	0
Saga	0	2	0	3	0
Sagi	0	0	0	3	0
Scal	0	0	0	3	0
Schig	0	0	0	3	0
Schip	3	0	3	0	0
Schis	0	0	3	0	0
Schiv	3	0	3	0	3
Scle	0	0	0	3	0
Scol	0	0	0	3	0
Scolo	0	0	0	3	0
Scrua	0	0	3	0	3
Scruo	0	3	3	0	3
Semi	0	0	3	0	0
Serp	0	0	0	3	0
Spham	0	0	0	3	0
Sphap	0	0	0	0	0
Sphas	0	0	0	3	0
Spio	0	0	0	3	0
Spiop	0	0	0	3	0
Spiro	0	0	0	3	0
Steno	0	0	3	0	0
Stenu	0	0	3	0	0
Sthe	0	0	0	3	0
Stre	0	0	0	0	0
Subad	0	0	0	3	0
Syco	0	0	0	1	3
Sylld	0	0	0	3	0
Sylls	0	0	0	3	0
Sync	0	0	3	0	0
Tanap	0	0	3	0	0
Tanas	0	0	3	0	0
Telm	0	0	3	0	0
Tere	0	0	0	3	0
Terg	0	0	0	3	0
Thar	0	0	0	3	0
Thec	0	0	0	3	0
Thel	0	0	0	3	0
Thia	0	3	3	0	0
Torn	0	3	3	0	0
Trav	0	0	0	3	0

Trit	0	0	0	3	0
Tryp	0	0	3	0	0
Tryph	0	0	3	0	0
Tubu	3	0	3	1	0
Tubul	0	3	0	3	3
Turb	0	3	3	0	1
Unci	0	0	3	0	0
Upog	0	0	3	0	2
Urot	0	0	3	0	0
Urti	0	2	0	3	0
Verr	0	0	3	0	0
Vesi	1	0	0	3	2

Table C-4 Fecundity (no. of larvae/propagules) traits table

Taxa	10	10-1000	1000-1M	>1M
Abie	0	0	0	0
Ablu	3	0	0	0
Acan	0	0	3	3
Ache	0	0	0	0
Acid	3	0	0	0
Acti	1	1	1	1
Adal	0	0	3	0
Aeoli	1	1	1	1
Aequ	0	0	0	3
Aete	2	2	0	0
Alcyd	0	3	0	0
Alcym	1	1	1	1
Alcyo	2	2	0	0
Amae	0	0	3	0
Amat	2	2	0	0
Ampe	3	1	0	0
Amphar	0	0	2	3
Amphib	2	2	0	0
Amphic	0	0	2	3
Amphil	3	0	0	0
Amphip	3	0	0	0
Amphur	0	0	3	0
Anap	0	0	3	0
Anom	1	1	1	1
Anop	0	0	0	0
Anth	3	1	0	0
Aoni	0	3	3	0
Aorid	1	1	1	1
Aphe	3	3	1	0
Aphr	0	0	3	3
Aply	1	1	1	1
Apse	3	0	0	0
Arac	1	1	1	1
Arca	0	0	0	0
Aric	0	0	0	0
Asc	0	0	0	0
Ascl	0	0	0	0
Asdil	0	0	0	0
Aspi	2	2	0	0
Ast	1	1	1	1
Asta	0	0	0	0
Atel	1	1	1	1

Athe	0	0	0	0
Axiu	0	0	0	0
Ba	1	1	1	1
Barn	0	0	0	0
Bath	3	0	0	0
Bice	2	2	0	0
Boug	0	0	0	0
Brac	1	1	1	1
Bran	3	0	0	0
Bucc	0	0	3	0
Busk	1	1	1	1
Caec	3	0	0	0
Calla	0	0	2	3
Calli	0	3	2	0
Callo	2	2	0	0
Callp	0	0	0	0
Calyc	1	1	1	1
Campa	1	1	1	1
Canc	0	0	2	3
Capit	1	1	1	1
Carc	0	0	3	0
Caul	0	0	3	0
CCa	3	0	0	0
Cell	2	2	0	0
Cellrel	2	2	0	0
Cera	0	0	0	0
Ceri	0	0	0	0
Chaep	0	0	3	0
Chaez	0	0	3	0
Chei	3	0	0	0
Chor	2	2	0	0
Cirr	0	0	0	0
Clio	1	1	1	1
Clym	3	0	0	0
Clyti	1	1	1	1
Conop	2	2	0	0
Cop	1	1	1	1
Coro	1	3	0	0
Corye	0	0	0	0
Coryt	1	1	1	1
Crang	0	2	3	0
Crepi	0	0	3	0
Cres	3	0	0	0
Crib	1	1	1	1
Crisa	2	2	0	0

Crisu	0	0	0	0
Cten	1	1	1	1
Cuma	1	1	1	1
Dend	0	0	0	0
Dendr	0	0	3	0
Diad	1	1	1	1
Dide	0	0	0	0
Diod	0	0	0	0
Dip	1	1	1	1
Disp	2	2	0	0
Dori	1	1	1	1
Doto	0	0	3	0
Dril	0	0	0	0
Dyop	0	0	0	0
Ebal	0	2	3	0
Echin	1	1	1	1
Echiu	0	0	0	0
Ectop	1	1	1	1
Edwa	0	0	0	0
Elect	2	2	0	0
Embl	0	0	0	0
Ephe	0	0	0	0
Epit	1	1	1	1
Erict	3	0	0	0
Eschl	2	2	0	0
Eschn	2	2	0	0
Eteo	0	0	3	0
Eual	0	0	3	0
Eubr	2	3	0	0
Eucl	3	0	0	0
Euden	1	1	1	1
Euhete	0	0	0	3
Eula	0	0	3	0
Eumid	0	0	3	0
Eune	0	0	3	2
Eupo	0	0	3	1
Eury	3	1	0	0
Eusp	0	3	3	0
Eusy	3	2	0	0
Exog	3	0	0	0
Fabu	1	1	1	1
Facel	1	2	0	0
Fili	1	1	1	1
Filo	0	0	0	0
Flab	0	0	0	0

Gala	0	1	3	0
Galat	0	0	0	0
Gammd	0	3	0	0
Gammp	3	0	0	0
Gatt	0	0	1	3
Gibb	2	3	0	0
Gita	1	1	1	1
Glyce	0	0	0	3
Glyci	0	0	3	0
Glycy	0	0	0	0
Gnath	3	1	0	0
Golf	3	3	0	0
Gonia	0	0	3	0
Gonir	0	0	0	0
Good	0	0	0	0
Gwyn	3	0	0	0
Gypt	0	0	3	1
Hagi	0	0	0	0
Hale	0	0	0	0
Haplo	3	2	0	0
Harm	0	0	3	3
Harp	0	0	0	0
Hart	3	0	0	0
Hesi	0	0	3	0
Heteb	1	1	1	1
Heten	1	1	1	1
Hinc	0	0	0	0
Hippa	2	2	0	0
Hippy	0	0	3	0
Holo	0	0	0	0
Hyas	0	2	3	0
Hydr	1	1	1	1
Hydra	0	0	0	0
Hype	1	1	1	1
Idot	3	1	0	0
Ione	0	0	0	0
Iph	3	0	0	0
Ischy	1	1	1	1
Isop	1	1	1	1
Janu	0	0	0	0
Jass	3	0	0	0
Jsm	1	3	0	0
Kell	0	0	3	3
Kirc	0	0	0	0
Kurt	0	3	0	0

Lagi	0	0	0	0
Lago	0	0	0	0
Lani	0	0	2	3
Laom	1	1	1	1
Laoni	0	3	0	0
Lepi	0	0	1	3
Lepidepecre	1	1	1	1
Leptr	3	0	0	0
Leptt	0	2	3	0
Leucs	1	1	1	1
Leuct	3	0	0	0
Limac	0	0	0	0
Lioca	0	0	3	3
Lipa	1	1	1	1
Lumb	1	1	1	1
Lysid	0	0	0	0
Lysin	1	1	1	1
Macr	0	2	3	0
Macro	0	0	0	0
Maer	3	0	0	0
Mage	0	3	2	0
Majo	1	1	1	1
Mald	0	0	0	0
Malm	0	0	0	0
Marp	0	0	0	0
Medi	1	3	3	0
Meli	1	1	1	1
Meto	3	0	0	0
Metr	1	1	1	1
Micrel	2	2	0	0
Microm	0	0	0	0
Micros	0	0	0	0
Microt	3	0	0	0
Micrth	0	0	0	0
Mima	0	0	0	0
Molg	1	1	1	1
Mya	0	0	0	3
Myria	1	1	1	1
Mys	0	0	3	0
Mysi	3	2	0	0
Myti	0	0	0	3
Neme	1	1	1	1
Neoa	0	0	3	3
Neog	0	2	0	0
Nepha	3	3	0	0

Nephy	0	0	3	0
Nered	1	1	1	1
Neres	0	0	3	3
Nicol	0	3	1	0
Nicom	3	0	0	0
Noem	0	0	0	0
Nole	2	2	0	0
Noth	1	1	1	1
Notom	0	2	3	0
Notot	3	2	0	0
Nucu	0	0	0	3
Nymph	0	0	0	0
Obel	1	1	1	1
Odon	3	2	0	0
Oligo	0	0	0	0
Onch	1	1	1	1
Onco	0	0	0	0
Ophe	0	0	3	3
Ophi	1	1	1	1
Ophioct	0	0	0	0
Ostra	0	0	0	0
Ostre	0	0	0	3
Otho	0	0	0	0
Owen	0	0	3	1
Oxyd	0	1	2	1
Pagur	1	1	1	1
Palae	0	0	3	0
Pand	0	0	3	0
Panda	2	3	2	0
Pant	0	3	0	0
Parad	3	2	0	0
Param	0	0	0	0
Paran	0	0	3	0
Pari	3	0	0	0
Pecti	1	1	1	1
Pedi	1	1	1	1
Perf	3	2	0	0
Perk	0	0	0	0
Peta	3	0	0	0
Phae	1	1	1	1
Phas	3	3	0	0
Pher	0	0	0	0
Phia	0	0	0	0
Pholi	0	3	0	0
Pholo	0	0	3	0

Phor	0	0	0	0
Phot	3	0	0	0
Phti	3	0	0	0
Phyla	0	0	0	0
Phyld	0	0	3	0
Pilu	0	1	3	0
Pinn	1	1	1	1
Pisid	1	3	0	0
Pisin	0	0	3	0
Pist	0	0	2	3
Plag	2	2	0	0
Plat	1	1	1	1
Pleuc	0	0	0	0
Pleun	0	0	3	0
Plum	0	0	0	0
Poda	0	0	0	0
Podo	0	0	0	0
Poec	0	3	2	0
Polyca	0	0	0	0
Polyce	1	2	0	0
Polyci	0	0	2	3
Polyd	2	3	3	0
Polyg	0	1	3	0
Polynd	1	1	1	1
Polyne	0	0	0	0
Porc	0	2	0	0
Pore	2	2	0	0
Port	0	0	3	0
Prax	0	0	0	0
Pria	1	1	1	1
Proce	1	1	1	1
Procs	0	0	0	0
Pros	0	0	3	0
Prot	3	3	0	0
Psamc	0	0	3	3
Psamt	0	0	0	0
Pseud	0	0	3	0
Pseul	2	3	0	0
Pseur	3	0	0	0
Pseut	0	0	3	0
Puel	2	2	0	0
Pygo	0	3	2	0
Pyra	1	1	1	1
Rasp	0	0	0	0
Rept	0	0	0	0

Riss	0	2	3	0
Sab	0	3	3	0
Sabed	1	1	1	1
Saber	0	0	3	2
Sacc	0	0	0	0
Saga	1	1	1	1
Sagi	0	0	0	0
Scal	0	0	0	0
Schig	3	3	0	0
Schip	2	2	0	0
Schis	0	0	0	0
Schiv	2	2	0	0
Scle	0	0	0	0
Scol	0	3	3	0
Scolo	0	1	3	0
Scrua	2	2	0	0
Scruo	2	2	0	0
Semi	1	1	1	0
Serp	1	1	1	1
Spham	0	0	0	0
Sphap	0	0	0	0
Sphas	3	1	0	0
Spio	2	3	3	0
Spiop	0	3	3	0
Spiro	0	3	0	0
Steno	3	0	0	0
Stenu	1	1	1	1
Sthe	0	0	3	3
Stre	0	0	0	0
Subad	3	2	1	3
Syco	1	1	1	1
Sylld	0	0	0	0
Sylls	3	2	0	0
Sync	3	0	0	0
Tanap	0	0	0	0
Tanas	0	0	0	0
Telm	1	1	1	1
Tere	1	1	1	1
Terg	0	3	0	0
Thar	0	0	0	0
Thec	0	0	0	0
Thel	0	0	2	3
Thia	0	0	0	0
Torn	0	0	0	0
Trav	0	0	3	3

Trit	1	1	1	1
Tryp	1	2	0	0
Tryph	3	0	0	0
Tubu	2	2	0	0
Tubul	1	1	1	1
Turb	2	2	0	0
Unci	3	0	0	0
Upog	0	0	3	0
Urot	3	0	0	0
Urti	1	1	1	1
Verr	1	1	1	1
Vesi	2	2	0	0

Table C-5 Feeding mode (Graz = grazer, nsDF = non-selective deposit, Pred = predator, S = suspension, Scav = scavanger, sDF = selective deposit) traits table

Taxa	Graz	nsDF	Pred	S	Scav	sDF
Abie	0	0	3	3	0	0
Ablu	0	0	0	0	0	3
Acan	3	0	3	0	0	0
Ache	3	0	3	0	2	1
Acid	0	0	3	0	0	0
Acti	0	0	2	3	0	0
Adal	3	0	0	0	0	0
Aeoli	3	0	3	0	0	0
Aequ	0	0	0	3	0	0
Aete	0	0	0	3	0	0
Alcyd	0	0	0	3	0	0
Alcym	0	0	1	3	0	0
Alcyo	0	0	0	3	0	0
Amae	0	0	0	0	0	3
Amat	0	0	0	3	0	0
Ampe	0	0	0	3	0	3
Amphar	0	3	0	3	0	3
Amphib	0	0	0	3	0	0
Amphic	0	0	0	0	0	3
Amphil	0	2	0	0	0	2
Amphip	0	0	0	3	0	0
Amphur	0	0	0	3	0	3
Anap	0	0	0	1	3	3
Anom	0	0	0	3	0	0
Anop	3	0	3	0	2	1
Anth	0	0	0	0	0	3
Aoni	0	3	0	0	0	3
Aorid	0	1	0	3	0	0
Aphe	0	0	0	0	0	3
Aphr	0	0	3	0	0	0
Aply	0	0	0	3	0	0
Apse	0	0	0	3	0	3
Arac	0	0	0	3	0	0
Arca	0	0	0	3	0	0
Aric	0	1	0	0	0	3
Asc	0	0	0	3	0	0
Ascl	0	3	0	0	0	3
Asdil	0	0	0	3	0	0
Aspi	0	0	0	3	0	0
Ast	0	0	1	0	1	1
Asta	0	0	0	3	0	0

Atel	0	0	3	0	0	0
Athe	0	0	0	0	0	3
Axiu	0	0	0	0	0	0
Ba	0	0	0	3	0	0
Barn	0	0	0	3	0	0
Bath	0	3	0	0	0	3
Bice	0	0	0	3	0	0
Boug	0	0	3	3	0	0
Brac	0	0	3	0	0	0
Bran	0	0	0	3	0	0
Bucc	0	0	3	0	0	0
Busk	0	0	0	3	0	0
Caec	1	0	0	0	0	3
Calla	0	3	0	0	0	0
Calli	3	0	0	0	0	3
Callo	0	0	0	3	0	0
Callp	3	0	3	0	2	1
Calyc	0	0	3	3	0	0
Campa	0	0	3	3	0	0
Canc	0	0	3	0	0	0
Capit	0	3	0	0	0	2
Carc	1	0	3	0	1	0
Caul	0	0	0	0	0	3
CCa	3	0	3	3	0	0
Cell	0	0	0	3	0	0
Cellrel	0	0	0	3	0	0
Cera	0	0	0	3	0	0
Ceri	0	0	2	3	0	0
Chaep	0	0	0	3	0	0
Chaez	0	0	0	2	0	3
Chei	0	0	0	0	0	3
Chor	0	0	0	3	0	0
Cirr	0	0	0	1	0	3
Clio	0	0	0	3	0	0
Clym	0	3	0	0	0	0
Clyti	0	0	3	3	0	0
Conop	0	0	0	3	0	0
Cop	0	0	0	1	0	0
Coro	1	2	0	2	0	2
Corye	0	0	3	3	0	0
Coryt	0	0	2	3	0	0
Crang	0	0	3	0	0	0
Crepi	0	0	0	3	0	0
Cres	0	0	0	0	0	3
Crib	0	0	0	3	0	0

Crisa	0	0	0	3	0	0
Crisu	0	0	0	3	0	0
Cten	0	0	3	0	3	0
Cuma	0	1	0	1	0	1
Dend	0	0	0	3	0	0
Dendr	3	0	3	0	0	0
Diad	0	0	3	0	0	0
Dide	0	0	0	3	0	0
Diod	3	0	0	0	0	0
Dip	0	0	0	3	0	0
Disp	0	0	0	3	0	0
Dori	3	0	0	0	0	0
Doto	3	0	3	0	0	0
Dril	0	0	2	0	2	1
Dyop	0	0	0	3	0	0
Ebal	0	0	3	0	1	1
Echin	0	1	0	0	0	1
Echiu	0	0	0	2	0	0
Ectop	0	0	1	3	0	0
Edwa	0	0	2	3	0	0
Elect	0	0	0	3	0	0
Embl	3	0	3	0	0	0
Ephe	0	0	0	0	0	3
Epit	0	0	3	0	0	0
Erict	0	2	0	3	0	0
Eschl	0	0	0	3	0	0
Eschn	0	0	0	3	0	0
Eteo	0	0	3	0	3	0
Eual	0	0	3	0	1	0
Eubr	3	0	3	0	0	0
Eucl	0	3	0	0	0	0
Euden	0	0	3	3	0	0
Euhete	0	0	0	3	0	0
Eula	0	0	3	0	3	0
Eumid	0	0	3	0	3	0
Eune	0	0	0	0	0	3
Eupo	0	0	0	0	0	3
Eury	0	0	3	0	0	0
Eusp	0	0	3	0	0	0
Eusy	2	0	2	0	2	0
Exog	2	0	0	0	3	3
Fabu	0	2	0	3	0	2
Facel	3	0	2	0	0	0
Fili	0	0	3	3	0	0
Filo	0	0	0	3	0	0

Flab	0	0	0	0	0	3
Gala	0	0	3	0	0	0
Galat	0	0	0	3	0	3
Gammd	0	0	0	0	0	3
Gammp	0	0	0	0	0	3
Gatt	0	0	3	0	0	0
Gibb	3	0	0	0	0	3
Gita	0	2	0	0	0	0
Glyce	0	0	3	0	3	1
Glyci	0	0	3	0	3	0
Glycy	0	0	0	3	0	0
Gnath	0	0	0	0	0	0
Golf	0	2	0	0	0	2
Gonia	0	0	3	0	3	0
Gonir	3	0	0	0	0	0
Good	0	0	0	3	0	0
Gwyn	0	0	0	0	0	0
Gypt	0	0	2	0	2	0
Hagi	0	0	0	3	0	0
Hale	0	0	3	3	0	0
Haplo	2	0	2	0	2	0
Harm	0	0	3	0	0	0
Harp	0	3	0	0	0	2
Hart	0	0	0	3	0	0
Hesi	0	0	3	0	3	0
Heteb	1	0	1	0	0	0
Heten	0	0	0	3	0	0
Hinc	0	0	0	0	0	0
Hippa	0	0	0	3	0	0
Hippy	0	0	3	0	1	0
Holo	0	0	0	3	0	0
Hyas	0	0	3	0	1	1
Hydr	0	0	0	3	0	0
Hydra	0	0	3	3	0	0
Hype	0	0	3	0	0	0
Idot	3	2	3	0	1	3
Ione	0	0	0	0	0	0
Iph	0	0	3	0	0	1
Ischy	0	0	0	2	0	2
Isop	0	0	1	0	1	1
Janu	0	0	0	0	0	0
Jass	0	2	0	3	0	0
Jsm	0	0	0	3	0	0
Kell	0	0	0	3	0	0
Kirc	0	0	0	3	0	0

Kurt	0	3	0	3	0	3
Lagi	0	3	0	0	0	0
Lago	0	3	0	0	0	0
Lani	0	0	0	3	0	3
Laom	0	0	3	3	0	0
Laoni	0	0	0	0	0	3
Lepi	0	0	3	0	3	3
Lepidepecre	0	0	3	0	1	0
Leptr	0	0	0	3	0	3
Leptt	3	0	0	0	0	3
Leucs	0	0	0	3	0	0
Leuct	0	3	0	0	0	3
Limac	3	0	3	0	0	0
Lioca	0	0	3	0	1	0
Lipa	0	0	3	0	0	0
Lumb	1	1	2	0	2	1
Lysid	0	0	0	0	1	2
Lysin	0	0	3	0	2	0
Macr	0	0	3	0	0	0
Macro	0	0	0	2	0	3
Maer	0	0	0	0	0	1
Mage	0	0	0	2	0	3
Majo	0	0	3	0	1	1
Mald	0	3	0	0	0	0
Malm	0	0	3	0	0	0
Marp	0	0	1	0	1	2
Medi	0	3	0	0	0	2
Meli	0	1	0	1	0	1
Meto	0	0	0	0	0	3
Metr	0	0	2	3	0	0
Micrel	0	0	0	3	0	0
Microm	0	0	0	0	0	0
Micros	0	0	0	0	0	3
Microt	0	3	2	0	0	0
Micrth	0	0	0	0	0	2
Mima	0	0	0	3	0	0
Molg	0	0	0	3	0	0
Mya	0	0	0	3	0	0
Myria	2	0	3	0	0	0
Mys	0	0	3	0	3	0
Mysi	0	0	2	1	1	1
Myti	0	0	0	3	0	0
Neme	0	0	3	0	2	0
Neoa	0	0	0	0	0	3
Neog	0	0	3	0	3	0

Nepha	0	2	0	0	0	2
Nephy	0	0	3	0	3	1
Nered	0	0	3	1	3	3
Neres	0	0	3	1	3	3
Nicol	0	0	0	0	0	3
Nicom	0	3	0	0	0	0
Noem	0	0	0	0	0	0
Nole	0	0	0	3	0	0
Noth	0	0	2	0	2	1
Notom	0	3	0	0	0	2
Notot	0	0	2	1	1	1
Nucu	0	3	0	0	0	3
Nymph	3	0	3	0	2	1
Obel	0	0	3	3	0	0
Odon	2	0	2	0	2	0
Oligo	0	3	0	0	0	0
Onch	3	0	3	0	0	0
Onco	0	0	0	3	0	0
Ophe	0	3	0	0	0	3
Ophi	0	1	1	1	1	1
Ophioct	0	0	3	0	2	0
Ostra	0	0	0	1	1	1
Ostre	0	0	0	3	0	0
Otho	0	0	0	0	0	0
Owen	0	0	0	3	0	3
Oxyd	0	3	0	0	0	3
Pagur	0	0	0	1	3	3
Palae	0	0	2	0	0	0
Pand	0	0	3	0	2	0
Panda	0	0	3	0	0	0
Pant	0	0	2	0	2	0
Parad	0	1	0	0	0	2
Param	0	3	0	0	0	2
Paran	0	0	3	0	3	0
Pari	0	0	0	3	0	3
Pecti	0	0	0	1	0	0
Pedi	0	0	0	3	0	0
Perf	0	0	2	1	1	1
Perk	0	0	0	3	0	0
Peta	0	3	0	0	0	0
Phae	0	0	2	1	1	1
Phas	0	2	0	0	0	2
Pher	0	0	0	2	0	3
Phia	0	0	3	3	0	0
Pholi	0	0	3	0	0	0

Pholo	0	0	3	0	0	0
Phor	0	0	0	3	0	0
Phot	0	3	0	2	0	0
Phti	0	1	3	0	0	0
Phyla	0	0	0	0	0	0
Phyld	0	0	3	0	3	0
Pilu	0	0	2	0	2	0
Pinn	0	0	0	0	2	0
Pisid	0	0	3	0	0	0
Pisin	0	0	3	0	0	0
Pist	0	0	0	0	0	3
Plag	0	0	0	3	0	0
Plat	0	0	3	0	0	0
Pleuc	0	0	3	0	0	0
Pleun	0	0	3	0	0	0
Plum	0	0	3	3	0	0
Poda	0	0	2	0	2	0
Podo	1	2	0	2	0	0
Poec	0	3	0	3	0	3
Polyca	0	0	0	3	0	0
Polyce	3	0	2	0	0	0
Polyci	0	0	0	0	0	3
Polyd	0	0	0	0	0	3
Polyg	0	1	0	0	0	1
Polynd	0	0	3	0	0	0
Polyne	0	0	0	0	0	0
Porc	0	0	0	2	1	2
Pore	0	0	0	3	0	0
Port	2	0	3	0	3	0
Prax	0	3	0	0	0	0
Pria	0	1	3	0	2	0
Proce	2	0	2	0	2	0
Procs	0	0	0	0	0	0
Pros	2	2	2	2	2	2
Prot	2	0	2	0	2	0
Psamc	3	0	3	0	0	0
Psamt	0	0	2	0	2	0
Pseud	0	0	3	0	3	0
Pseul	0	0	0	0	0	3
Pseur	0	1	3	0	0	0
Pseut	0	0	0	3	0	0
Puel	0	0	0	3	0	0
Pygo	0	0	0	3	0	3
Pyra	0	0	3	0	0	0
Rasp	0	0	0	3	0	0

Rept	0	0	0	0	0	0
Riss	2	1	0	0	0	3
Sab	0	0	0	3	0	0
Sabed	0	0	0	3	0	0
Saber	0	0	0	3	0	0
Sacc	0	1	0	1	0	1
Saga	0	0	2	3	0	0
Sagi	0	0	1	0	0	0
Scal	0	3	0	0	0	3
Schig	2	0	2	0	2	2
Schip	0	0	0	3	0	0
Schis	0	0	0	3	0	0
Schiv	0	0	0	3	0	0
Scle	0	0	0	0	0	0
Scol	0	0	0	0	0	3
Scolo	0	3	0	0	0	2
Scrua	0	0	0	3	0	0
Scruo	0	0	0	3	0	0
Semi	0	0	0	3	0	0
Serp	0	0	0	1	0	0
Spham	0	0	0	0	0	3
Sphap	0	0	0	0	0	0
Sphas	2	0	0	0	0	3
Spio	0	0	0	0	0	3
Spiop	0	3	0	3	0	3
Spiro	0	0	0	3	0	0
Steno	1	0	0	0	0	3
Stenu	0	0	0	0	0	3
Sthe	0	0	3	0	3	0
Stre	0	0	0	0	0	0
Subad	0	0	3	0	0	0
Syco	0	0	0	3	0	0
Sylld	0	0	2	0	2	0
Sylls	2	0	2	0	2	0
Sync	0	2	1	0	1	2
Tanap	0	0	0	0	0	3
Tanas	0	0	0	0	0	0
Telm	0	0	2	1	1	1
Tere	0	1	0	1	0	1
Terg	0	0	3	0	0	0
Thar	0	0	0	2	0	3
Thec	3	0	0	0	0	0
Thel	0	0	0	0	0	3
Thia	0	0	3	0	0	0
Torn	2	0	0	0	0	3

Trav	0	3	0	0	0	0
Trit	0	0	2	1	1	1
Tryp	0	0	3	0	2	0
Tryph	0	0	3	0	2	0
Tubu	0	0	0	3	0	0
Tubul	0	0	3	3	0	0
Turb	0	0	0	3	0	0
Unci	0	3	0	1	0	1
Upog	0	3	0	3	0	3
Urot	0	3	0	0	0	3
Urti	0	0	2	3	0	0
Verr	0	0	0	3	0	0
Vesi	0	0	0	3	0	0

Table C-6 Habitat engineering traits table

Taxa	Destabiliser	None	Reef	Stabiliser
Abie	0	0	3	0
Ablu	1	2	0	1
Acan	0	3	0	0
Ache	0	3	0	0
Acid	2	1	0	0
Acti	0	3	0	0
Adal	0	3	0	0
Aeoli	0	3	0	0
Aequ	0	1	3	0
Aete	0	0	3	0
Alcyd	0	3	0	0
Alcym	0	0	3	0
Alcyo	0	0	3	0
Amae	0	2	1	2
Amat	0	0	3	0
Ampe	0	0	0	3
Amphar	0	1	2	3
Amphib	0	0	3	0
Amphic	0	1	2	3
Amphil	1	1	0	1
Amphip	0	3	0	0
Amphur	3	0	0	0
Anap	1	0	3	0
Anom	0	0	3	0
Anop	0	3	0	0
Anth	0	3	0	0
Aoni	0	2	1	3
Aorid	0	1	0	2
Aphe	0	2	0	2
Aphr	2	2	0	0
Aply	1	2	1	0
Apse	2	3	0	0
Arac	1	2	1	0
Arca	0	2	3	0
Aric	0	3	0	3
Asc	0	1	3	0
Ascl	3	0	0	0
Asdil	0	1	3	0
Aspi	0	0	3	0
Ast	1	2	1	0
Asta	0	0	0	0
Atel	3	0	3	0

Athe	0	2	1	3
Axiu	0	3	0	0
Ba	0	0	3	0
Barn	0	3	0	0
Bath	3	2	0	0
Bice	0	0	3	0
Boug	0	0	2	0
Brac	0	3	0	0
Bran	2	2	0	0
Bucc	2	0	3	0
Busk	1	2	1	0
Caec	1	1	0	0
Calla	3	0	0	0
Calli	0	3	2	0
Callo	0	0	3	0
Callp	0	3	0	0
Calyc	0	0	3	0
Campa	0	0	3	0
Canc	3	0	3	0
Capit	3	0	0	2
Carc	1	2	1	0
Caul	0	2	0	2
CCa	0	3	0	0
Cell	0	0	3	0
Cellrel	0	0	3	0
Cera	0	3	0	0
Ceri	0	0	0	3
Chaep	0	0	3	3
Chaez	0	2	0	2
Chei	1	3	0	0
Chor	0	0	3	0
Cirr	0	2	0	2
Clio	0	0	3	0
Clym	0	0	0	3
Clyti	0	0	3	0
Conop	0	0	3	0
Cop	1	2	1	0
Coro	1	2	1	3
Corye	0	0	3	0
Coryt	0	3	0	0
Crang	1	3	0	0
Crepi	0	0	3	0
Cres	0	3	0	0
Crib	1	2	1	0
Crisa	0	0	3	0

Crisu	0	0	0	0
Cten	0	3	0	0
Cuma	1	2	1	0
Dend	0	1	3	0
Dendr	0	3	0	0
Diad	0	3	0	0
Dide	0	1	3	0
Diod	0	3	0	0
Dip	0	3	0	0
Disp	0	0	3	0
Dori	1	2	1	0
Doto	0	3	0	0
Dril	2	1	0	0
Dyop	0	3	0	2
Ebal	0	2	1	0
Echin	1	2	1	0
Echiu	3	0	0	0
Ectop	0	0	3	0
Edwa	0	1	0	3
Elect	0	0	3	0
Embl	0	3	0	0
Ephe	0	3	0	0
Epit	0	3	0	0
Erict	2	0	0	3
Eschl	0	0	3	0
Eschn	0	0	3	0
Eteo	2	2	0	0
Eual	1	3	0	0
Eubr	0	3	0	0
Eucl	0	0	0	3
Euden	0	0	3	0
Euhete	1	2	1	0
Eula	2	2	0	0
Eumid	2	2	0	0
Eune	1	2	0	2
Eupo	0	2	1	2
Eury	1	2	0	0
Eusp	3	1	0	0
Eusy	1	2	0	0
Exog	1	2	0	0
Fabu	1	2	1	0
Facel	0	3	0	0
Fili	0	0	3	0
Filo	0	0	0	0
Flab	3	1	0	0

Gala	0	3	0	0
Galat	0	0	1	3
Gammd	0	3	0	0
Gammp	0	3	0	0
Gatt	2	2	0	0
Gibb	0	2	2	0
Gita	1	2	1	0
Glyce	2	1	0	2
Glyci	2	1	0	2
Glycy	0	1	3	0
Gnath	0	3	0	0
Golf	0	0	0	3
Gonia	2	1	0	2
Gonir	0	0	0	0
Good	2	2	0	1
Gwyn	0	0	0	0
Gypt	2	2	0	0
Hagi	0	0	0	0
Hale	0	0	3	0
Haplo	1	2	0	0
Harm	2	2	0	0
Harp	3	0	0	0
Hart	1	2	1	0
Hesi	2	2	0	0
Heteb	0	3	0	0
Heten	0	0	3	0
Hinc	0	0	0	0
Hippa	0	0	3	0
Hippy	1	3	0	0
Holo	0	0	0	0
Hyas	0	0	3	0
Hydr	1	2	1	0
Hydra	0	0	3	0
Hype	0	3	0	0
Idot	1	2	0	0
Ione	0	3	0	0
Iph	1	3	0	0
Ischy	2	2	0	2
Isop	1	2	1	0
Janu	0	0	0	0
Jass	3	3	0	0
Jsm	0	0	2	2
Kell	0	3	2	0
Kirc	0	3	0	0
Kurt	2	2	0	1

Lagi	0	0	1	3
Lago	0	0	0	0
Lani	0	2	1	2
Laom	0	0	3	0
Laoni	0	2	1	3
Lepi	2	2	0	0
Lepidepecre	0	3	0	0
Leptr	0	0	0	3
Leptt	0	3	0	0
Leucs	0	0	3	0
Leuct	1	2	0	0
Limac	0	3	0	0
Lioca	1	3	0	0
Lipa	0	3	0	0
Lumb	2	2	0	0
Lysid	2	3	0	0
Lysin	0	3	0	0
Macr	0	0	3	0
Macro	0	3	0	0
Maer	3	0	0	3
Mage	1	0	0	3
Majo	0	2	2	0
Mald	0	0	0	3
Malm	2	2	0	0
Marp	2	3	0	0
Medi	3	0	0	2
Meli	1	2	0	1
Meto	1	3	0	0
Metr	0	3	0	0
Micrel	0	0	3	0
Microm	0	3	0	0
Micros	0	2	1	3
Microt	2	3	0	2
Micrth	2	2	0	0
Mima	0	0	0	0
Molg	0	0	0	3
Mya	2	1	0	2
Myria	1	2	0	0
Mys	2	2	0	0
Mysi	0	2	0	2
Myti	0	0	3	0
Neme	1	2	1	0
Neoa	0	2	1	2
Neog	0	3	0	0
Nepha	0	3	0	3

Nephy	3	0	0	0
Nered	1	2	0	2
Neres	1	2	0	2
Nicol	0	2	1	2
Nicom	0	0	0	3
Noem	0	0	0	0
Nole	0	0	3	0
Noth	2	1	0	0
Notom	3	0	0	2
Notot	0	3	0	0
Nucu	2	0	0	0
Nymph	0	3	0	0
Obel	0	0	3	0
Odon	1	2	0	0
Oligo	2	1	0	0
Onch	0	3	0	0
Onco	0	0	0	0
Ophe	3	0	0	0
Ophi	1	2	1	0
Ophioct	2	2	0	0
Ostra	0	0	0	0
Ostre	0	0	3	0
Otho	0	0	0	0
Owen	0	0	1	3
Oxyd	2	2	1	0
Pagur	1	0	3	0
Palae	0	3	0	0
Pand	0	3	0	0
Panda	1	3	0	0
Pant	1	2	1	0
Parad	0	3	0	3
Param	3	0	0	0
Paran	2	2	0	0
Pari	0	3	0	0
Pecti	0	1	3	0
Pedi	1	2	1	0
Perf	0	1	2	0
Perk	0	3	0	0
Peta	0	0	0	3
Phae	1	2	1	0
Phas	0	0	0	3
Pher	3	1	0	0
Phia	0	0	3	0
Pholi	1	2	1	0
Pholo	3	3	0	0

Phor	0	3	0	0
Phot	0	3	0	0
Phti	0	3	0	0
Phyla	0	0	0	0
Phyld	2	2	0	0
Pilu	0	0	3	0
Pinn	0	3	0	0
Pisid	0	0	3	0
Pisin	2	2	0	0
Pist	0	2	1	2
Plag	0	0	3	0
Plat	1	2	1	0
Pleuc	0	3	0	0
Pleun	0	3	0	0
Plum	0	0	3	0
Poda	2	2	0	0
Podo	1	2	0	0
Poec	0	0	0	3
Polyca	0	1	3	0
Polyce	0	3	0	0
Polyci	0	2	1	2
Polyd	0	2	1	3
Polyg	0	3	0	0
Polynd	2	2	0	0
Polyne	0	0	0	0
Porc	1	2	1	0
Pore	0	0	3	0
Port	0	3	0	0
Prax	0	0	0	3
Pria	0	3	0	0
Proce	1	2	0	0
Procs	0	0	0	0
Pros	1	2	1	0
Prot	1	1	0	0
Psamc	0	3	0	0
Psamt	2	2	0	0
Pseud	2	2	0	0
Pseul	0	2	1	3
Pseur	0	3	0	0
Pseut	0	0	2	2
Puel	0	0	3	0
Pygo	0	2	1	3
Pyra	0	3	0	0
Rasp	0	0	0	0
Rept	0	0	0	0

Riss	2	2	0	0
Sab	0	0	2	2
Sabed	0	0	2	2
Saber	0	0	3	0
Sacc	2	2	0	0
Saga	0	3	0	0
Sagi	0	3	0	0
Scal	3	0	0	0
Schig	1	1	0	0
Schip	0	0	3	0
Schis	0	3	0	0
Schiv	0	0	3	0
Scle	0	0	0	0
Scol	0	2	1	3
Scolo	3	0	0	0
Scrua	0	0	3	0
Scruo	0	0	3	0
Semi	0	0	3	0
Serp	0	3	0	0
Spham	0	3	0	0
Sphap	0	0	0	0
Sphas	1	2	0	0
Spio	0	2	1	3
Spiop	0	2	1	3
Spiro	0	0	2	0
Steno	1	3	0	0
Stenu	1	3	0	0
Sthe	2	2	0	0
Stre	0	0	0	0
Subad	2	2	0	0
Syco	0	3	0	0
Sylld	2	2	0	0
Sylls	1	2	0	0
Sync	3	0	0	0
Tanap	2	1	0	0
Tanas	0	0	0	0
Telm	0	3	0	0
Tere	1	2	1	0
Terg	0	3	0	0
Thar	0	2	0	2
Thec	0	0	0	0
Thel	0	2	1	2
Thia	3	0	0	0
Torn	0	3	0	0
Trav	3	0	0	0

Trit	1	2	1	0
Tryp	0	3	0	0
Tryph	0	3	0	0
Tubu	0	0	3	0
Tubul	0	0	3	0
Turb	0	0	3	0
Unci	2	0	0	2
Upog	3	0	0	0
Urot	3	0	0	0
Urti	0	3	0	0
Verr	0	0	3	0
Vesi	0	0	3	0

Table C-7 Larval development (D = direct, Lc = lecithotrophic, Pk = Planktotrophic) traits table

Taxa	D	Lc	Pk
Abie	0	0	3
Ablu	3	0	0
Acan	0	3	0
Ache	2	0	0
Acid	3	0	0
Acti	0	0	3
Adal	0	3	0
Aeoli	0	1	0
Aequ	0	0	3
Aete	0	3	0
Alcyd	0	3	0
Alcym	0	0	3
Alcyo	0	1	0
Amae	0	3	1
Amat	0	1	0
Ampe	3	0	0
Amphar	3	0	0
Amphib	0	3	0
Amphic	1	0	0
Amphil	3	0	0
Amphip	2	2	0
Amphur	0	0	3
Anap	0	0	3
Anom	0	0	3
Anop	3	0	0
Anth	3	0	0
Aoni	0	0	3
Aorid	3	0	0
Aphe	3	3	0
Aphr	3	0	0
Aply	1	1	2
Apse	3	0	0
Arac	1	1	2
Arca	0	0	1
Aric	3	0	0
Asc	0	1	0
Ascl	0	0	1
Asdil	0	1	0
Aspi	0	3	0
Ast	0	3	3
Asta	3	0	1

Atel	0	0	3
Athe	0	0	1
Axiu	0	0	3
Ba	0	0	3
Barn	0	0	3
Bath	3	0	0
Bice	0	3	0
Boug	0	0	3
Brac	0	0	3
Bran	0	0	3
Bucc	3	0	0
Busk	0	2	0
Caec	0	0	3
Calla	0	0	3
Calli	3	0	0
Callo	0	3	0
Callp	2	0	0
Calyc	3	0	0
Campa	0	0	1
Canc	0	0	3
Capit	1	1	1
Carc	0	0	3
Caul	3	0	0
CCa	3	0	0
Cell	0	1	0
Cellrel	0	3	0
Cera	0	0	3
Ceri	0	0	3
Chaep	0	0	3
Chaez	0	3	0
Chei	3	0	0
Chor	0	3	0
Cirr	2	1	0
Clio	0	0	3
Clym	0	3	0
Clyti	0	0	1
Conop	0	3	0
Cop	0	3	0
Coro	2	0	0
Corye	0	0	3
Coryt	0	0	3
Crang	0	0	3
Crepi	0	0	3
Cres	3	0	0
Crib	0	3	0

Crisa	0	3	0
Crisu	0	0	0
Cten	1	1	2
Cuma	1	0	0
Dend	0	1	0
Dendr	0	3	0
Diad	0	0	3
Dide	0	1	0
Diod	3	0	0
Dip	0	3	0
Disp	0	3	0
Dori	0	0	3
Doto	0	3	0
Dril	0	1	0
Dyop	3	0	0
Ebal	0	0	3
Echin	0	0	3
Echiu	0	0	3
Ectop	0	0	3
Edwa	0	0	3
Elect	0	3	0
Embl	0	3	0
Ephe	3	3	0
Epit	0	0	3
Erict	3	0	0
Eschl	0	3	0
Eschn	0	3	0
Eteo	0	0	3
Eual	0	0	3
Eubr	0	0	3
Eucl	0	3	0
Euden	0	0	3
Euhete	0	3	3
Eula	0	0	3
Eumid	0	0	3
Eune	1	0	0
Eupo	0	3	0
Eury	3	0	0
Eusp	3	0	3
Eusy	3	0	0
Exog	3	0	0
Fabu	0	0	3
Facel	2	2	0
Fili	0	0	3
Filo	3	0	0

Flab	2	0	0
Gala	0	0	3
Galat	0	0	3
Gammd	3	0	0
Gammp	3	0	0
Gatt	0	0	3
Gibb	0	0	1
Gita	1	1	2
Glyce	0	0	3
Glyci	0	3	0
Glycy	0	0	3
Gnath	3	0	0
Golf	0	0	3
Gonia	0	3	0
Gonir	0	0	3
Good	0	0	1
Gwyn	3	0	0
Gypt	0	0	3
Hagi	0	0	0
Hale	1	0	1
Haplo	1	0	0
Harm	0	0	3
Harp	3	0	0
Hart	1	1	2
Hesi	0	0	3
Heteb	0	0	3
Heten	0	0	3
Hinc	0	3	0
Hippa	0	3	0
Hippy	0	0	3
Holo	0	0	0
Hyas	0	0	3
Hydr	0	3	0
Hydra	0	1	0
Hype	1	0	1
Idot	3	0	0
Ione	1	0	0
Iph	3	0	0
Ischy	3	0	0
Isop	1	0	0
Janu	0	0	0
Jass	3	0	0
Jsm	1	1	0
Kell	0	0	3
Kirc	0	0	0

Kurt	0	0	3
Lagi	0	0	3
Lago	0	0	0
Lani	3	3	3
Laom	0	0	1
Laoni	0	0	3
Lepi	0	0	3
Lepidepecre	3	0	0
Leptr	3	0	0
Leptt	0	0	3
Leucs	0	0	3
Leuct	3	0	0
Limac	0	1	0
Lioca	0	0	3
Lipa	1	1	2
Lumb	3	0	0
Lysid	0	1	1
Lysin	3	0	0
Macr	0	0	3
Macro	1	1	1
Maer	3	0	0
Mage	0	0	3
Majo	0	0	3
Mald	3	0	3
Malm	0	0	3
Marp	0	3	0
Medi	0	0	3
Meli	3	0	0
Meto	3	0	0
Metr	0	0	3
Micrel	0	3	0
Microm	0	0	0
Micros	3	0	0
Microt	3	0	0
Micrth	0	1	1
Mima	0	0	3
Molg	0	1	0
Mya	0	0	3
Myria	3	0	3
Mys	0	3	1
Mysi	3	0	0
Myti	1	0	3
Neme	3	3	3
Neoa	0	3	0
Neog	1	1	0

Nepha	3	0	0
Nephy	0	0	3
Nered	3	1	0
Neres	3	1	0
Nicol	3	3	0
Nicom	3	0	0
Noem	0	0	0
Nole	0	3	0
Noth	1	0	0
Notom	0	0	3
Notot	3	0	0
Nucu	0	0	3
Nymph	2	0	0
Obel	0	0	1
Odon	3	0	0
Oligo	0	0	0
Onch	0	3	0
Onco	0	0	0
Ophe	0	3	0
Ophi	0	0	3
Ophioct	0	0	3
Ostra	0	0	1
Ostre	0	0	3
Otho	0	0	0
Owen	0	0	3
Oxyd	3	0	2
Pagur	0	0	3
Palae	0	0	3
Pand	0	2	2
Panda	0	0	3
Pant	0	0	3
Parad	1	0	0
Param	3	0	0
Paran	0	0	1
Pari	3	0	0
Pecti	0	0	1
Pedi	3	0	0
Perf	3	0	0
Perk	0	0	0
Peta	3	0	0
Phae	1	1	2
Phas	0	1	0
Pher	2	0	2
Phia	0	0	3
Pholi	0	3	0

Pholo	0	3	3
Phor	0	0	3
Phot	3	0	0
Phti	3	0	0
Phyla	0	0	0
Phyld	0	3	3
Pilu	0	0	3
Pinn	0	0	3
Pisid	0	0	3
Pisin	0	0	3
Pist	0	3	0
Plag	0	1	0
Plat	3	3	3
Pleuc	0	0	0
Pleun	1	1	2
Plum	0	0	1
Poda	0	1	3
Podo	3	0	0
Poec	0	0	3
Polyca	0	1	0
Polyce	2	2	0
Polyci	0	3	0
Polyd	0	0	3
Polyg	0	0	1
Polynd	0	0	2
Polyne	0	0	0
Porc	0	0	3
Pore	0	3	0
Port	0	0	3
Prax	3	0	0
Pria	1	1	2
Proce	1	0	0
Procs	0	0	0
Pros	2	2	2
Prot	3	0	0
Psamc	0	0	3
Psamt	0	2	0
Pseud	0	0	1
Pseul	0	0	3
Pseur	3	0	0
Pseut	0	3	0
Puel	0	3	0
Pygo	3	0	3
Pyra	1	1	2
Rasp	0	0	0

Rept	0	0	0
Riss	0	0	3
Sab	0	3	0
Sabed	1	1	0
Saber	0	0	3
Sacc	3	0	0
Saga	0	0	3
Sagi	1	0	2
Scal	0	3	0
Schig	0	3	0
Schip	0	3	0
Schis	3	0	0
Schiv	0	3	0
Scle	0	0	0
Scol	0	0	3
Scolo	0	3	0
Scrua	0	3	0
Scruo	0	3	0
Semi	1	1	2
Serp	0	0	2
Spham	3	3	0
Sphap	0	0	0
Sphas	3	0	0
Spio	1	0	3
Spiop	0	0	3
Spiro	0	1	2
Steno	3	0	0
Stenu	3	0	0
Sthe	0	0	3
Stre	0	0	0
Subad	0	0	2
Syco	1	1	2
Sylld	0	1	3
Sylls	3	0	1
Sync	3	0	0
Tanap	3	0	0
Tanas	0	0	0
Telm	1	1	2
Tere	1	1	1
Terg	0	3	0
Thar	3	0	0
Thec	0	0	3
Thel	3	3	0
Thia	0	0	3
Torn	0	0	3

Trav	3	0	0
Trit	0	3	0
Tryp	3	0	0
Tryph	3	0	0
Tubu	0	3	0
Tubul	0	0	3
Turb	0	1	0
Unci	3	0	0
Upog	0	0	3
Urot	3	0	0
Urti	0	3	0
Verr	0	0	3
Vesi	0	1	0

Table C-8 Larval duration traits table

Taxa	None	1	2-15	16-30	31-60	60
Abie	0	0	0	0	0	0
Ablu	3	0	0	0	0	0
Acan	0	0	3	1	0	0
Ache	3	0	0	0	0	0
Acid	3	0	0	0	0	0
Acti	1	0	1	1	1	0
Adal	0	1	3	1	0	0
Aeoli	1	0	1	1	1	0
Aequ	0	0	2	3	1	0
Aete	1	0	1	1	1	0
Alcyd	0	3	0	0	0	0
Alcym	1	0	1	1	1	0
Alcyo	1	0	1	1	1	0
Amae	0	1	3	1	0	0
Amat	1	0	1	1	1	0
Ampe	3	0	0	0	0	0
Amphar	3	2	1	0	0	0
Amphib	0	0	0	0	0	0
Amphic	3	2	1	0	0	0
Amphil	3	0	0	0	0	0
Amphip	3	0	0	0	0	0
Amphur	0	0	3	2	3	3
Anap	0	0	2	3	1	0
Anom	1	0	1	1	1	0
Anop	0	0	0	0	0	0
Anth	3	0	0	0	0	0
Aoni	0	0	3	0	0	0
Aorid	1	0	1	1	1	0
Aphe	3	2	3	0	0	0
Aphr	2	3	1	0	0	0
Aply	1	0	1	1	1	0
Apse	3	0	0	0	0	0
Arac	1	0	1	1	1	0
Arca	0	0	0	0	0	0
Aric	0	0	0	0	0	0
Asc	0	0	3	0	0	0
Ascl	0	0	0	0	0	0
Asdil	0	0	0	0	0	0
Aspi	0	0	0	0	0	0
Ast	1	0	1	1	1	0
Asta	3	0	0	0	0	0
Atel	0	0	1	3	3	2

Athe	0	0	0	0	0	0
Axiu	0	0	0	0	0	0
Ba	1	0	1	1	1	0
Barn	0	0	0	0	0	0
Bath	3	0	0	0	0	0
Bice	0	0	0	0	0	0
Boug	0	0	0	0	0	0
Brac	1	0	1	1	1	0
Bran	0	0	0	1	3	3
Bucc	3	0	0	0	0	0
Busk	1	0	1	1	1	0
Caec	0	0	0	3	3	0
Calla	0	0	0	2	3	1
Calli	3	0	0	0	0	0
Callo	1	0	1	1	1	0
Callp	3	0	0	0	0	0
Calyc	1	0	1	1	1	0
Campa	1	0	1	1	1	0
Canc	0	0	1	3	2	0
Capit	1	0	1	1	1	0
Carc	0	0	1	2	2	1
Caul	3	0	0	0	0	0
CCa	3	0	0	0	0	0
Cell	0	0	0	0	0	0
Cellrel	1	0	1	1	1	0
Cera	0	0	0	0	0	0
Ceri	0	0	0	0	0	3
Chaep	0	0	0	3	2	0
Chaez	3	0	0	0	0	0
Chei	3	0	0	0	0	0
Chor	0	0	0	0	0	0
Cirr	0	0	0	0	0	0
Clio	1	0	1	1	1	0
Clym	0	1	3	0	0	0
Clyti	1	0	1	1	1	0
Conop	1	0	1	1	1	0
Cop	1	0	1	1	1	0
Coro	1	0	1	1	1	0
Corye	0	0	0	0	0	0
Coryt	1	0	1	1	1	0
Crang	0	0	0	1	3	2
Crepi	0	0	0	1	3	0
Cres	3	0	0	0	0	0
Crib	1	0	1	1	1	0
Crisa	0	0	0	0	0	0

Crisu	0	0	0	0	0	0
Cten	1	0	1	1	1	0
Cuma	1	0	1	1	1	0
Dend	0	3	1	0	0	0
Dendr	0	0	0	3	3	0
Diad	1	0	1	1	1	0
Dide	0	0	0	0	0	0
Diod	3	0	0	0	0	0
Dip	1	0	1	1	1	0
Disp	0	0	0	0	0	0
Dori	1	0	1	1	1	0
Doto	0	0	3	3	0	0
Dril	0	0	0	0	0	0
Dyop	0	0	0	0	0	0
Ebal	0	0	0	2	3	2
Echin	1	0	1	1	1	0
Echiu	0	0	0	0	0	0
Ectop	1	0	1	1	1	0
Edwa	0	0	0	0	0	0
Elect	1	0	1	1	1	0
Embl	0	0	0	0	0	0
Ephe	0	3	0	0	0	0
Epit	3	0	0	0	0	0
Erict	3	0	0	0	0	0
Eschl	0	0	0	0	0	0
Eschn	0	0	0	0	0	0
Eteo	0	0	3	3	1	0
Eual	0	0	0	2	3	1
Eubr	0	0	3	1	0	0
Eucl	3	1	3	0	0	0
Euden	1	0	1	1	1	0
Euhete	0	0	0	0	3	0
Eula	0	0	0	0	1	3
Eumid	0	0	0	0	1	3
Eune	0	0	3	1	0	0
Eupo	0	1	3	0	0	0
Eury	3	0	0	0	0	0
Eusp	3	0	0	1	3	0
Eusy	2	3	0	0	0	0
Exog	3	0	0	0	0	0
Fabu	0	0	2	2	0	0
Facel	2	2	2	0	0	0
Fili	1	0	1	1	1	0
Filo	3	0	0	0	0	0
Flab	3	0	0	0	0	0

Gala	0	0	0	2	3	2
Galat	0	0	0	0	0	0
Gammd	1	0	1	1	1	0
Gammp	3	0	0	0	0	0
Gatt	0	0	0	2	3	0
Gibb	3	1	3	1	0	0
Gita	1	0	1	1	1	0
Glyce	0	0	0	0	3	2
Glyci	3	0	0	1	3	0
Glycy	0	0	2	3	1	0
Gnath	3	0	0	0	0	0
Golf	3	2	3	0	0	0
Gonia	3	0	0	1	3	0
Gonir	0	0	0	0	0	3
Good	3	0	0	0	0	0
Gwyn	3	0	0	0	0	0
Gypt	0	2	3	0	0	0
Hagi	0	0	0	0	0	0
Hale	0	0	0	0	0	0
Haplo	3	0	0	0	0	0
Harm	0	0	0	2	3	0
Harp	0	0	0	0	0	0
Hart	1	0	1	1	1	0
Hesi	0	0	0	0	1	3
Heteb	1	0	1	1	1	0
Heten	1	0	1	1	1	0
Hinc	0	0	0	0	0	0
Hippa	0	0	0	0	0	0
Hippy	0	0	1	3	1	0
Holo	0	0	0	0	0	0
Hyas	0	0	0	3	3	0
Hydr	0	3	0	0	0	0
Hydra	0	0	0	0	0	0
Hype	1	0	1	1	1	0
Idot	3	0	0	0	0	0
Ione	0	0	0	0	0	0
Iph	3	0	0	0	0	0
Ischy	1	0	1	1	1	0
Isop	1	0	1	1	1	0
Janu	0	0	0	0	0	0
Jass	3	0	0	0	0	0
Jsm	0	0	3	1	0	0
Kell	0	0	0	0	1	3
Kirc	0	0	0	0	0	0
Kurt	0	0	3	3	1	0

Lagi	0	0	0	0	0	0
Lago	0	0	0	0	0	0
Lani	0	0	0	2	3	1
Laom	1	0	1	1	1	0
Laoni	0	0	3	3	3	0
Lepi	0	0	0	2	3	0
Lepidepecre	1	0	1	1	1	0
Leptr	3	0	0	0	0	0
Leptt	0	3	3	0	0	0
Leucs	1	0	1	1	1	0
Leuct	3	0	0	0	0	0
Limac	0	0	0	0	0	0
Lioca	0	0	0	2	3	2
Lipa	1	0	1	1	1	0
Lumb	1	0	1	1	1	0
Lysid	0	0	3	1	0	0
Lysin	1	0	1	1	1	0
Macr	0	0	1	3	2	0
Macro	0	0	0	0	0	0
Maer	3	0	0	0	0	0
Mage	0	0	0	3	3	1
Majo	1	0	1	1	1	0
Mald	0	0	0	0	0	0
Malm	0	0	0	0	0	0
Marp	0	3	0	0	0	0
Medi	0	0	0	3	1	0
Meli	1	0	1	1	1	0
Meto	3	0	0	0	0	0
Metr	0	1	3	0	0	0
Micrel	1	0	1	1	1	0
Microm	0	0	0	0	0	0
Micros	0	0	0	0	0	0
Microt	3	0	0	0	0	0
Micrth	0	0	0	0	0	0
Mima	0	0	0	0	0	0
Molg	0	3	1	0	0	0
Mya	0	0	2	3	2	0
Myria	1	0	1	1	1	0
Mys	0	0	0	0	1	3
Mysi	3	0	0	0	0	0
Myti	2	0	1	3	1	0
Neme	1	0	1	1	1	0
Neoa	0	1	3	1	0	0
Neog	0	0	0	1	1	0
Nepha	3	2	2	0	0	0

Nephy	0	0	0	3	3	1
Nered	1	0	1	1	1	0
Neres	0	0	1	3	1	0
Nicol	3	0	0	0	0	0
Nicom	3	0	0	0	0	0
Noem	0	0	0	0	0	0
Nole	0	0	0	0	0	0
Noth	1	0	1	1	1	0
Notom	0	1	3	0	0	0
Notot	3	0	0	0	0	0
Nucu	0	3	3	1	0	0
Nymph	0	0	0	0	0	0
Obel	1	0	1	1	1	0
Odon	3	0	0	0	0	0
Oligo	0	0	0	0	0	0
Onch	1	0	1	1	1	0
Onco	0	0	0	0	0	0
Ophe	0	1	3	1	0	0
Ophi	1	0	1	1	1	0
Ophioct	0	0	0	0	0	0
Ostra	0	0	0	0	0	0
Ostre	0	0	2	3	0	0
Otho	0	0	0	0	0	0
Owen	0	0	3	3	1	0
Oxyd	3	3	1	1	2	1
Pagur	1	0	1	1	1	0
Palae	0	0	0	0	3	0
Pand	0	0	0	0	2	2
Panda	0	0	2	3	1	0
Pant	0	0	2	2	2	0
Parad	3	0	0	0	0	0
Param	0	0	0	0	0	0
Paran	0	0	0	0	1	3
Pari	3	0	0	0	0	0
Pecti	1	0	1	1	1	0
Pedi	1	0	1	1	1	0
Perf	3	0	0	0	0	0
Perk	0	0	0	0	0	0
Peta	3	0	0	0	0	0
Phae	1	0	1	1	1	0
Phas	2	2	3	0	0	0
Pher	3	0	0	0	0	0
Phia	0	0	0	0	0	0
Pholi	1	0	1	1	1	0
Pholo	0	0	0	3	1	0

Phor	0	0	0	0	0	0
Phot	3	0	0	0	0	0
Phti	3	0	0	0	0	0
Phyla	0	0	0	0	0	0
Phyld	0	0	0	0	1	3
Pilu	0	0	1	3	2	0
Pinn	0	0	1	3	2	0
Pisid	0	0	0	2	3	1
Pisin	0	0	0	0	1	3
Pist	0	1	3	1	0	0
Plag	0	0	0	0	0	0
Plat	1	0	1	1	1	0
Pleuc	0	0	0	0	0	0
Pleun	1	0	1	1	1	0
Plum	0	0	0	0	0	0
Poda	0	0	0	0	0	0
Podo	0	0	0	0	0	0
Poec	0	0	0	1	3	0
Polyca	0	3	0	0	0	0
Polyce	2	2	2	0	0	0
Polyci	0	1	3	1	0	0
Polyd	0	0	2	3	3	0
Polyg	0	1	3	0	0	0
Polynd	1	0	1	1	1	0
Polyne	0	0	0	0	0	0
Porc	0	0	0	0	2	2
Pore	0	0	0	0	0	0
Port	0	0	0	0	2	0
Prax	0	0	0	0	0	0
Pria	1	0	1	1	1	0
Proce	1	0	1	1	1	0
Procs	0	0	0	0	0	0
Pros	1	0	1	0	1	1
Prot	3	0	0	0	0	0
Psamc	0	0	0	3	3	1
Psamt	0	0	0	0	0	0
Pseud	0	0	0	0	1	3
Pseul	0	0	3	3	3	0
Pseur	3	0	0	0	0	0
Pseut	0	0	3	1	0	0
Puel	0	0	0	0	0	0
Pygo	3	3	3	3	3	0
Pyra	1	0	1	1	1	0
Rasp	0	0	0	0	0	0
Rept	0	0	0	0	0	0

Riss	1	0	1	1	1	0
Sab	0	0	3	1	0	0
Sabed	1	0	1	1	1	0
Saber	0	0	0	0	1	3
Sacc	0	0	0	0	0	0
Saga	1	0	1	1	1	0
Sagi	1	0	2	2	0	0
Scal	3	0	0	0	0	0
Schig	0	0	3	0	0	0
Schip	0	0	0	0	0	0
Schis	0	0	0	0	0	0
Schiv	1	0	1	1	1	0
Scle	0	0	0	0	0	0
Scol	0	0	3	3	3	0
Scolo	3	0	0	0	0	0
Scrua	1	0	1	1	1	0
Scruo	0	0	0	0	0	0
Semi	0	0	0	0	2	2
Serp	1	0	1	1	1	0
Spham	3	0	0	0	0	0
Sphap	0	0	0	0	0	0
Sphas	3	0	0	0	0	0
Spio	3	1	3	0	0	0
Spiop	0	0	3	3	3	0
Spiro	0	0	2	2	2	0
Steno	3	0	0	0	0	0
Stenu	1	0	1	1	1	0
Sthe	0	0	0	3	3	0
Stre	0	0	0	0	0	0
Subad	0	0	0	2	3	0
Syco	1	0	1	1	1	0
Sylld	0	0	0	0	0	0
Sylls	0	1	3	0	0	0
Sync	3	0	0	0	0	0
Tanap	0	0	0	0	0	0
Tanas	0	0	0	0	0	0
Telm	1	0	1	1	1	0
Tere	1	0	1	1	1	0
Terg	1	0	1	1	1	0
Thar	0	0	0	0	0	0
Thec	0	0	0	0	0	0
Thel	3	1	1	0	0	0
Thia	0	0	0	2	3	1
Torn	0	0	0	0	0	0
Trav	3	1	1	0	0	0

Trit	0	0	3	0	0	0
Tryp	3	0	0	0	0	0
Tryph	3	0	0	0	0	0
Tubu	0	0	0	0	0	0
Tubul	1	0	1	1	1	0
Turb	0	0	0	0	0	0
Unci	3	0	0	0	0	0
Upog	0	0	2	3	1	0
Urot	3	0	0	0	0	0
Urti	0	0	3	1	0	0
Verr	1	0	1	1	1	0
Vesi	0	0	0	0	0	0

Table C-9 Longevity (years) traits table

Taxa	1	10	1-2	3-10
Abie	0	0	1	3
Ablu	1	0	1	0
Acan	0	0	0	1
Ache	0	0	0	1
Acid	1	0	2	0
Acti	0	2	0	1
Adal	3	0	1	0
Aeoli	0	0	0	1
Aequ	0	0	0	3
Aete	1	0	1	0
Alcyd	3	0	0	0
Alcym	0	3	0	0
Alcyo	0	0	0	3
Amae	3	0	1	0
Amat	1	0	1	0
Ampe	0	0	3	0
Amphar	0	0	0	3
Amphib	1	0	1	0
Amphic	0	0	3	0
Amphil	1	0	1	0
Amphip	0	0	0	3
Amphur	0	3	0	0
Anap	0	0	0	3
Anom	0	1	0	1
Anop	0	0	0	1
Anth	0	0	1	0
Aoni	3	0	0	0
Aorid	1	0	1	0
Aphe	0	0	0	3
Aphr	0	0	0	3
Aply	1	0	1	1
Apse	0	0	1	0
Arac	1	0	1	1
Arca	0	1	0	1
Aric	0	0	1	0
Asc	0	0	2	3
Ascl	0	0	1	0
Asdil	0	0	2	2
Aspi	1	0	1	0
Ast	0	1	0	1
Asta	0	0	0	1
Atel	0	0	3	0

Athe	0	0	1	0
Axiu	0	0	0	0
Ba	0	0	0	3
Barn	0	0	0	0
Bath	3	0	1	0
Bice	1	0	1	0
Boug	0	0	0	1
Brac	0	0	0	1
Bran	0	0	0	1
Bucc	0	2	0	0
Busk	1	0	1	1
Caec	0	0	0	1
Calla	0	0	3	0
Calli	0	0	0	1
Callo	1	0	1	0
Callp	0	0	0	1
Calyc	0	0	0	1
Campa	1	0	0	0
Canc	0	3	0	0
Capit	0	0	1	0
Carc	0	0	0	3
Caul	0	0	0	3
CCa	1	0	0	0
Cell	1	0	0	0
Cellrel	1	0	1	0
Cera	0	0	0	3
Ceri	0	3	0	0
Chaep	0	0	0	1
Chaez	0	0	3	0
Chei	1	0	0	0
Chor	1	0	1	0
Cirr	0	0	0	1
Clio	0	0	0	1
Clym	3	0	1	0
Clyti	1	0	0	0
Conop	1	0	1	0
Cop	1	0	0	0
Coro	3	0	0	0
Corye	0	0	0	1
Coryt	0	2	0	1
Crang	0	0	0	3
Crepi	0	0	0	1
Cres	1	0	1	0
Crib	1	0	1	1
Crisa	1	0	1	0

Crisu	0	0	0	0
Cten	0	0	0	3
Cuma	3	0	1	0
Dend	0	0	2	0
Dendr	0	0	0	1
Diad	1	0	1	1
Dide	0	0	1	1
Diod	0	3	0	0
Dip	3	0	0	0
Disp	1	0	1	0
Dori	3	0	0	0
Doto	0	0	0	1
Dril	0	0	1	1
Dyop	1	0	0	0
Ebal	0	0	3	0
Echin	0	0	0	1
Echiu	0	0	0	1
Ectop	1	0	1	1
Edwa	0	3	0	1
Elect	1	0	1	0
Embl	0	0	0	1
Ephe	0	0	1	0
Epit	0	0	0	1
Erict	1	0	1	0
Eschl	1	0	1	0
Eschn	0	3	0	0
Eteo	0	0	3	0
Eual	0	0	1	0
Eubr	3	0	1	0
Eucl	0	0	1	3
Euden	0	0	0	1
Euhete	0	3	0	0
Eula	0	0	1	1
Eumid	0	0	1	1
Eune	0	0	0	1
Eupo	0	0	0	3
Eury	0	0	3	0
Eusp	2	0	3	0
Eusy	0	0	1	0
Exog	0	0	1	0
Fabu	0	0	0	3
Facel	3	0	1	0
Fili	0	0	0	1
Filo	0	0	0	0
Flab	0	0	1	1

Gala	0	0	0	3
Galat	0	0	1	1
Gammd	3	0	0	0
Gammp	0	0	3	0
Gatt	0	0	0	3
Gibb	0	0	0	1
Gita	3	0	0	0
Glyce	0	0	0	3
Glyci	0	0	1	1
Glycy	0	3	0	0
Gnath	0	0	1	0
Golf	0	0	1	0
Gonia	0	0	3	1
Gonir	0	0	0	0
Good	0	0	0	1
Gwyn	0	0	0	0
Gypt	0	0	1	0
Hagi	0	0	0	0
Hale	0	0	0	1
Haplo	0	0	1	0
Harm	0	0	1	1
Harp	1	0	2	0
Hart	1	0	1	1
Hesi	0	0	1	1
Heteb	1	0	1	1
Heten	0	1	0	1
Hinc	0	0	0	0
Hippa	1	0	1	0
Hippy	0	0	3	0
Holo	0	0	0	0
Hyas	0	0	0	3
Hydr	1	0	1	1
Hydra	0	0	1	0
Hype	1	0	0	0
Idot	2	0	3	1
Ione	0	0	1	0
Iph	1	0	2	0
Ischy	1	0	1	0
Isop	0	0	1	0
Janu	0	0	0	0
Jass	1	0	1	0
Jsm	0	0	1	0
Kell	0	0	0	1
Kirc	0	0	0	0
Kurt	0	0	0	1

Lagi	0	0	3	0
Lago	0	0	0	0
Lani	0	0	3	0
Laom	1	0	0	0
Laoni	0	0	3	0
Lepi	0	0	1	0
Lepidepecre	1	0	2	0
Leptr	3	0	0	0
Leptt	0	0	0	1
Leucs	0	0	0	1
Leuct	1	0	1	0
Limac	0	0	0	1
Lioca	0	0	0	3
Lipa	0	0	3	0
Lumb	0	0	1	1
Lysid	0	0	1	0
Lysin	1	0	2	0
Macr	0	0	3	0
Macro	0	0	1	1
Maer	1	0	1	0
Mage	0	0	0	3
Majo	0	0	0	3
Mald	0	0	1	0
Malm	0	0	0	1
Marp	0	0	1	0
Medi	0	0	3	0
Meli	1	0	1	0
Meto	1	0	1	0
Metr	1	0	1	1
Micrel	1	0	1	0
Microm	0	0	0	0
Micros	0	0	1	0
Microt	0	0	1	0
Micrth	0	0	1	0
Mima	0	0	0	0
Molg	0	0	1	1
Mya	0	3	0	0
Myria	1	0	1	0
Mys	0	0	1	1
Mysi	3	0	3	0
Myti	0	1	0	0
Neme	0	0	3	2
Neoa	0	0	1	1
Neog	0	2	0	2
Nepha	0	0	1	0

Nephy	0	0	0	2
Nered	0	0	0	1
Neres	0	0	0	1
Nicol	3	0	1	0
Nicom	0	0	1	0
Noem	0	0	0	0
Nole	1	0	1	0
Noth	0	0	1	0
Notom	0	0	3	0
Notot	3	0	3	0
Nucu	0	0	0	3
Nymph	1	0	1	1
Obel	0	0	0	1
Odon	0	0	1	0
Oligo	0	0	1	0
Onch	0	0	0	1
Onco	0	0	0	0
Ophe	0	0	3	0
Ophi	0	0	0	3
Ophioct	0	0	0	1
Ostra	1	0	0	0
Ostre	0	0	0	3
Otho	0	0	0	0
Owen	0	0	0	3
Oxyd	1	0	3	0
Pagur	0	0	0	3
Palae	0	0	0	3
Pand	0	0	0	3
Panda	0	0	3	1
Pant	0	0	3	0
Parad	0	0	1	0
Param	1	0	2	0
Paran	0	0	1	1
Pari	1	0	0	0
Pecti	0	1	0	0
Pedi	0	0	1	1
Perf	3	0	3	0
Perk	0	0	0	0
Peta	0	0	1	0
Phae	1	1	0	3
Phas	0	0	1	0
Pher	0	0	0	1
Phia	0	0	0	1
Pholi	1	0	1	1
Pholo	0	0	0	3

Phor	0	0	1	0
Phot	0	0	1	0
Phti	1	0	0	0
Phyla	0	0	0	0
Phyld	0	0	0	1
Pilu	0	0	2	1
Pinn	0	0	1	1
Pisid	0	0	1	3
Pisin	0	0	0	3
Pist	0	0	1	1
Plag	1	0	1	0
Plat	0	0	1	0
Pleuc	0	0	0	0
Pleun	0	3	0	0
Plum	0	0	0	1
Poda	0	0	1	0
Podo	1	0	0	0
Poec	0	0	1	0
Polyca	0	0	0	1
Polyce	3	0	1	0
Polyci	0	0	0	3
Polyd	0	0	1	0
Polyg	1	0	3	0
Polynd	0	0	0	1
Polyne	0	0	0	0
Porc	0	0	2	3
Pore	1	0	1	0
Port	0	0	0	3
Prax	0	0	1	0
Pria	1	0	1	1
Proce	0	0	1	0
Procs	0	0	0	0
Pros	2	2	2	2
Prot	0	0	3	0
Psamc	0	0	0	3
Psamt	0	0	1	0
Pseud	0	0	1	1
Pseul	0	0	1	0
Pseur	1	0	0	0
Pseut	0	0	1	0
Puel	1	0	1	0
Pygo	0	0	1	0
Pyra	1	0	1	1
Rasp	0	0	0	0
Rept	0	0	0	0

Riss	1	0	1	1
Sab	0	0	1	0
Sabed	0	0	1	0
Saber	0	0	0	3
Sacc	1	0	0	0
Saga	0	3	0	1
Sagi	3	0	0	0
Scal	0	0	3	0
Schig	0	0	1	1
Schip	0	3	0	0
Schis	3	0	0	0
Schiv	1	0	1	0
Scle	0	0	0	0
Scol	0	0	1	0
Scolo	0	0	1	3
Scrua	1	0	1	0
Scruo	1	0	1	0
Semi	0	0	0	3
Serp	0	0	1	0
Spham	0	0	1	0
Sphap	0	0	0	0
Sphas	0	0	1	0
Spio	0	0	3	0
Spiop	0	0	3	0
Spiro	0	0	2	2
Steno	1	0	1	0
Stenu	1	0	1	0
Sthe	0	0	0	1
Stre	0	0	0	0
Subad	0	0	0	1
Syco	1	0	1	1
Sylld	0	0	1	0
Sylls	0	0	2	0
Sync	0	0	1	0
Tanap	0	0	1	0
Tanas	0	0	0	0
Telm	3	0	0	0
Tere	0	0	1	1
Terg	3	0	0	0
Thar	0	0	1	1
Thec	0	0	0	0
Thel	0	0	0	3
Thia	0	1	0	0
Torn	0	0	0	1
Trav	0	0	1	1

Trit	1	0	1	1
Tryp	3	0	0	0
Tryph	1	0	2	0
Tubu	1	0	1	0
Tubul	0	0	0	1
Turb	1	0	0	0
Unci	1	0	0	0
Upog	0	0	0	3
Urot	0	0	3	0
Urti	0	3	0	0
Verr	0	0	0	3
Vesi	1	0	1	0

Table C-10 Maximum adult size (mm) traits table

Taxa	10	11-100	101-200	>200
Abie	0	3	3	0
Ablu	3	0	0	0
Acan	0	3	0	0
Ache	3	0	0	0
Acid	3	3	0	0
Acti	2	3	0	0
Adal	1	3	0	0
Aeoli	0	3	3	0
Aequ	0	3	0	0
Aete	0	1	0	0
Alcyd	1	1	0	0
Alcym	0	0	0	3
Alcyo	1	1	1	0
Amae	0	3	0	0
Amat	0	3	0	0
Ampe	3	3	0	0
Amphar	0	3	0	0
Amphib	0	1	0	0
Amphic	0	3	0	0
Amphil	3	0	0	0
Amphip	0	2	0	0
Amphur	0	0	3	0
Anap	3	0	0	0
Anom	0	3	0	0
Anop	3	0	0	0
Anth	3	1	0	0
Aoni	0	3	0	0
Aorid	3	3	0	0
Aphe	0	3	0	0
Aphr	0	0	3	0
Aply	0	3	0	0
Apse	3	0	0	0
Arac	1	1	0	0
Arca	0	3	0	0
Aric	2	2	0	0
Asc	0	3	3	0
Ascl	0	3	0	0
Asdil	0	3	3	0
Aspi	0	1	0	0
Ast	0	3	3	3
Asta	0	3	0	0
Atel	0	3	0	0

Athe	0	3	0	0
Axiu	0	3	0	0
Ba	0	3	0	0
Barn	0	3	0	0
Bath	3	0	0	0
Bice	0	3	0	0
Boug	0	3	0	0
Brac	3	0	0	0
Bran	0	3	0	0
Bucc	0	3	3	0
Busk	3	0	0	0
Caec	3	0	0	0
Calla	0	3	0	0
Calli	0	3	0	0
Callo	0	3	0	0
Callp	3	0	0	0
Calyc	3	0	0	0
Campa	0	0	3	0
Canc	0	3	3	0
Capit	0	3	3	3
Carc	0	3	0	0
Caul	0	3	0	0
CCa	3	3	0	0
Cell	0	1	0	0
Cellrel	0	3	0	0
Cera	0	3	0	0
Ceri	0	0	3	0
Chaep	0	0	0	3
Chaez	0	3	0	0
Chei	3	3	0	0
Chor	0	1	0	0
Cirr	0	1	1	0
Clio	0	0	0	3
Clym	0	3	0	0
Clyti	3	3	0	0
Conop	1	2	1	0
Cop	3	0	0	0
Coro	3	1	0	0
Corye	0	3	0	0
Coryt	2	3	0	0
Crang	0	3	0	0
Crepi	0	3	0	0
Cres	3	0	0	0
Crib	2	1	0	0
Crisa	0	3	0	0

Crisu	0	3	0	0
Cten	0	1	3	0
Cuma	1	1	0	0
Dend	0	3	0	0
Dendr	0	3	0	0
Diad	0	3	0	0
Dide	3	3	0	0
Diod	0	3	0	0
Dip	3	0	0	0
Disp	0	3	0	0
Dori	0	1	3	0
Doto	3	3	0	0
Dril	0	0	3	1
Dyop	3	0	0	0
Ebal	0	3	0	0
Echin	0	1	1	0
Echiu	0	1	1	0
Ectop	3	2	0	0
Edwa	0	3	0	0
Elect	0	1	0	0
Embl	3	0	0	0
Ephe	3	0	0	0
Epit	0	3	0	0
Erict	3	0	0	0
Eschl	0	3	0	0
Eschn	0	1	0	0
Eteo	0	3	0	0
Eual	0	3	0	0
Eubr	3	3	0	0
Eucl	0	3	0	0
Euden	0	0	1	0
Euhete	0	3	3	0
Eula	0	3	1	0
Eumid	0	2	0	0
Eune	0	0	0	3
Eupo	0	3	3	0
Eury	3	0	0	0
Eusp	3	3	0	0
Eusy	3	0	0	0
Exog	3	0	0	0
Fabu	0	3	0	0
Facel	1	3	0	0
Fili	0	1	1	0
Filo	3	0	0	0
Flab	0	3	0	0

Gala	0	3	0	0
Galat	0	3	0	0
Gammd	3	0	0	0
Gammp	3	0	0	0
Gatt	0	3	0	0
Gibb	3	0	0	0
Gita	3	0	0	0
Glyce	0	2	3	1
Glyci	0	3	0	0
Glycy	0	3	0	0
Gnath	3	0	0	0
Golf	0	3	3	0
Gonia	0	3	0	0
Gonir	0	3	0	0
Good	3	0	0	0
Gwyn	2	1	0	0
Gypt	0	3	0	0
Hagi	0	0	0	0
Hale	0	3	0	0
Haplo	0	3	0	0
Harm	0	3	0	0
Harp	3	0	0	0
Hart	0	0	0	3
Hesi	3	0	0	0
Heteb	0	3	0	0
Heten	0	3	0	0
Hinc	0	0	0	0
Hippa	0	1	0	0
Hippy	0	3	0	0
Holo	0	0	2	2
Hyas	0	3	0	0
Hydr	0	3	0	0
Hydra	0	0	0	3
Hype	1	0	0	0
Idot	3	2	0	0
Ione	1	0	0	0
Iph	3	1	0	0
Ischy	3	0	0	0
Isop	1	1	0	0
Janu	3	0	0	0
Jass	3	0	0	0
Jsm	3	3	0	0
Kell	3	0	0	0
Kirc	0	3	1	0
Kurt	3	0	0	0

Lagi	0	3	0	0
Lago	3	0	0	0
Lani	0	0	0	3
Laom	0	0	3	0
Laoni	0	3	3	0
Lepi	0	3	0	0
Lepidepecre	3	3	0	0
Leptr	3	0	0	0
Leptt	3	0	0	0
Leucs	0	3	0	0
Leuct	3	0	0	0
Limac	0	3	0	0
Lioca	0	3	0	0
Lipa	0	0	3	0
Lumb	0	1	1	1
Lysid	0	0	3	0
Lysin	3	3	0	0
Macr	0	3	0	0
Macro	3	3	0	0
Maer	3	0	0	0
Mage	0	3	0	0
Majo	0	0	3	3
Mald	0	1	1	1
Malm	0	3	0	0
Marp	0	1	1	1
Medi	0	3	0	0
Meli	3	1	0	0
Meto	3	0	0	0
Metr	0	1	3	3
Micrel	0	3	0	0
Microm	3	0	0	0
Micros	0	3	0	0
Microt	3	0	0	0
Micrth	0	3	0	0
Mima	0	3	0	0
Molg	0	3	0	0
Mya	0	3	3	0
Myria	0	3	0	0
Mys	0	3	0	0
Mysi	2	3	0	0
Myti	0	3	0	0
Neme	0	1	1	1
Neoa	0	0	3	3
Neog	0	3	1	0
Nepha	0	3	0	0

Nephy	0	3	1	0
Nered	0	1	1	1
Neres	0	3	3	3
Nicol	0	3	0	0
Nicom	0	0	3	0
Noem	0	0	0	0
Nole	0	1	0	0
Noth	0	0	3	0
Notom	0	0	0	2
Notot	2	3	0	0
Nucu	0	3	0	0
Nymph	3	0	0	0
Obel	0	0	0	3
Odon	2	3	0	0
Oligo	0	0	0	0
Onch	0	1	0	0
Onco	1	3	0	0
Ophe	0	3	0	0
Ophi	0	1	3	0
Ophioct	0	3	0	0
Ostra	1	0	0	0
Ostre	0	3	1	0
Otho	0	0	0	0
Owen	0	3	0	0
Oxyd	1	3	1	0
Pagur	0	3	0	0
Palae	0	3	2	1
Pand	0	0	3	0
Panda	0	3	0	0
Pant	3	0	0	0
Parad	0	3	0	0
Param	3	0	0	0
Paran	0	2	0	0
Pari	3	0	0	0
Pecti	1	1	0	0
Pedi	3	3	0	0
Perf	2	3	0	0
Perk	0	3	0	0
Peta	0	3	0	0
Phae	0	0	1	3
Phas	0	3	0	0
Pher	0	3	0	0
Phia	3	0	0	0
Pholi	0	0	1	3
Pholo	0	3	0	0

Phor	0	3	3	0
Phot	3	0	0	0
Phti	0	3	0	0
Phyla	0	0	0	0
Phyld	0	0	2	2
Pilu	1	3	0	0
Pinn	3	1	0	0
Pisid	0	3	0	0
Pisin	2	3	0	0
Pist	0	3	0	0
Plag	3	3	0	0
Plat	0	1	0	0
Pleuc	3	0	0	0
Pleun	0	0	0	3
Plum	0	0	3	0
Poda	3	0	0	0
Podo	1	0	0	0
Poec	0	3	0	0
Polyca	0	3	0	0
Polyce	1	3	0	0
Polyci	0	3	0	0
Polyd	0	3	0	0
Polyg	0	3	0	0
Polynd	0	3	0	0
Polyne	0	0	0	0
Porc	3	3	0	0
Pore	0	1	1	0
Port	0	3	0	0
Prax	0	3	0	0
Pria	0	3	0	0
Proce	0	3	0	0
Procs	0	0	0	0
Pros	3	3	0	0
Prot	0	3	0	0
Psamc	0	3	0	0
Psamt	0	3	0	0
Pseud	2	2	0	0
Pseul	0	3	0	0
Pseur	0	3	0	0
Pseut	0	0	3	0
Puel	0	1	0	0
Pygo	0	3	0	0
Pyra	3	0	0	0
Rasp	0	0	3	0
Rept	0	0	0	0

Riss	3	1	0	0
Sab	0	3	3	3
Sabed	1	1	1	0
Saber	0	3	0	0
Sacc	1	0	0	0
Saga	0	2	2	0
Sagi	0	3	0	0
Scal	0	3	0	0
Schig	0	3	0	0
Schip	0	1	0	0
Schis	0	3	0	0
Schiv	0	3	0	0
Scle	0	0	0	0
Scol	0	3	3	0
Scolo	0	0	3	0
Scrua	0	1	0	0
Scruo	0	3	0	0
Semi	2	2	0	0
Serp	0	1	0	0
Spham	0	2	0	0
Sphap	0	0	0	0
Sphas	3	0	0	0
Spio	0	3	0	0
Spiop	0	3	0	0
Spiro	0	2	2	0
Steno	3	0	0	0
Stenu	3	0	0	0
Sthe	0	3	0	0
Stre	3	0	0	0
Subad	0	3	0	0
Syco	3	0	0	0
Sylld	3	0	0	0
Sylls	0	3	0	0
Sync	3	0	0	0
Tanap	3	0	0	0
Tanas	3	0	0	0
Telm	3	0	0	0
Tere	0	1	1	1
Terg	3	0	0	0
Thar	0	3	0	0
Thec	0	3	0	0
Thel	0	0	3	0
Thia	0	3	0	0
Torn	3	0	0	0
Trav	0	3	0	0

Trit	0	0	3	0
Tryp	3	0	0	0
Tryph	3	0	0	0
Tubu	0	3	0	0
Tubul	0	2	2	1
Turb	0	3	0	0
Unci	3	0	0	0
Upog	0	0	3	0
Urot	3	0	0	0
Urti	0	1	3	0
Verr	3	0	0	0
Vesi	0	0	0	2

Table C-11 Strategies for displacement traits table

Taxa	High	Low	Med
Abie	0	3	0
Ablu	2	0	2
Acan	3	0	3
Ache	0	0	3
Acid	2	0	2
Acti	1	3	0
Adal	0	1	3
Aeoli	2	0	3
Aequ	3	0	0
Aete	0	3	0
Alcyd	0	3	0
Alcym	0	3	0
Alcyo	0	3	0
Amae	2	2	3
Amat	0	3	0
Ampe	1	0	2
Amphar	0	3	0
Amphib	0	3	0
Amphic	0	3	0
Amphil	1	0	2
Amphip	2	0	3
Amphur	3	0	3
Anap	2	0	2
Anom	0	3	0
Anop	0	0	3
Anth	2	0	3
Aoni	0	3	2
Aorid	1	3	2
Aphe	0	3	1
Aphr	3	0	3
Aply	0	3	0
Apse	2	0	2
Arac	0	3	0
Arca	0	3	0
Aric	3	0	0
Asc	0	3	0
Ascl	0	1	2
Asdil	0	3	0
Aspi	0	3	0
Ast	2	0	3
Asta	0	3	2
Atel	0	0	3

Athe	0	1	2
Axiu	0	0	3
Ba	0	3	0
Barn	0	3	0
Bath	2	0	3
Bice	0	3	0
Boug	0	3	0
Brac	0	0	3
Bran	1	0	2
Bucc	2	0	3
Busk	0	3	0
Caec	2	0	3
Calla	3	0	3
Calli	0	0	3
Callo	0	3	0
Callp	0	0	3
Calyc	0	3	0
Campa	0	3	0
Canc	2	0	3
Capit	0	2	2
Carc	0	0	3
Caul	0	3	1
CCa	2	0	2
Cell	0	3	0
Cellrel	0	3	0
Cera	0	0	3
Ceri	0	3	1
Chaep	0	3	1
Chaez	0	3	1
Chei	1	0	2
Chor	0	3	0
Cirr	0	1	0
Clio	0	3	0
Clym	0	3	0
Clyti	0	3	0
Conop	0	3	0
Cop	2	1	0
Coro	1	0	3
Corye	0	3	0
Coryt	1	3	0
Crang	3	0	0
Crepi	0	3	0
Cres	2	0	2
Crib	0	3	0
Crisa	0	3	0

Crisu	0	3	0
Cten	3	0	0
Cuma	1	0	1
Dend	0	3	0
Dendr	2	0	3
Diad	0	3	0
Dide	0	3	0
Diod	0	0	3
Dip	0	3	0
Disp	0	3	0
Dori	0	0	3
Doto	2	0	3
Dril	3	0	0
Dyop	2	0	2
Ebal	2	0	3
Echin	3	0	3
Echiu	0	1	2
Ectop	0	3	0
Edwa	1	3	2
Elect	0	3	0
Embl	2	0	3
Ephe	0	0	1
Epit	2	0	3
Erict	1	3	2
Eschl	0	3	0
Eschn	0	3	0
Eteo	2	0	3
Eual	2	0	3
Eubr	0	0	3
Eucl	0	3	0
Euden	0	3	0
Euhete	0	2	1
Eula	2	0	1
Eumid	2	0	1
Eune	2	0	1
Eupo	0	3	0
Eury	1	0	3
Eusp	0	0	3
Eusy	0	2	1
Exog	1	0	1
Fabu	0	0	3
Facel	0	0	3
Fili	0	3	0
Filo	0	3	0
Flab	2	0	1

Gala	2	0	3
Galat	0	3	0
Gammd	1	0	2
Gammp	1	3	2
Gatt	2	1	3
Gibb	0	0	3
Gita	0	2	0
Glyce	3	0	2
Glyci	3	0	0
Glycy	2	3	3
Gnath	2	3	0
Golf	0	1	2
Gonia	3	0	0
Gonir	0	0	3
Good	0	1	1
Gwyn	0	3	0
Gypt	1	0	1
Hagi	0	3	0
Hale	0	3	0
Haplo	0	0	1
Harm	2	1	1
Harp	2	0	3
Hart	0	3	0
Hesi	2	0	1
Heteb	0	0	3
Heten	0	3	0
Hinc	0	3	0
Hippa	0	3	0
Hippy	2	0	3
Holo	0	3	0
Hyas	2	0	3
Hydr	0	3	0
Hydra	0	3	0
Hype	3	0	0
Idot	3	0	1
Ione	0	3	0
Iph	2	0	2
Ischy	1	1	2
Isop	0	1	3
Janu	0	3	0
Jass	1	3	2
Jsm	0	3	0
Kell	2	3	0
Kirc	0	3	0
Kurt	0	3	3

Lagi	0	3	0
Lago	0	3	0
Lani	0	3	1
Laom	0	3	0
Laoni	0	3	2
Lepi	2	0	1
Lepidepecre	2	0	2
Leptr	1	3	2
Leptt	0	0	3
Leucs	0	3	0
Leuct	1	0	2
Limac	0	0	3
Lioca	2	0	3
Lipa	3	0	0
Lumb	2	0	3
Lysid	2	0	1
Lysin	2	0	2
Macr	2	0	3
Macro	2	0	0
Maer	2	0	3
Mage	3	0	2
Majo	2	0	3
Mald	0	3	0
Malm	2	1	3
Marp	2	3	1
Medi	0	2	2
Meli	2	0	2
Meto	2	0	2
Metr	0	3	0
Micrel	0	3	0
Microm	0	0	3
Micros	0	1	2
Microt	1	3	2
Micrth	2	0	1
Mima	0	3	0
Molg	0	3	0
Mya	0	3	2
Myria	2	0	3
Mys	2	0	1
Mysi	0	2	2
Myti	0	3	0
Neme	2	0	3
Neoa	0	3	0
Neog	0	0	3
Nepha	0	1	2

Nephy	3	0	0
Nered	1	0	1
Neres	1	0	1
Nicol	0	3	1
Nicom	0	3	0
Noem	0	0	0
Nole	0	3	0
Noth	1	3	1
Notom	0	2	2
Notot	2	0	2
Nucu	2	3	3
Nymph	0	0	3
Obel	0	3	0
Odon	2	0	1
Oligo	0	1	1
Onch	0	0	3
Onco	0	3	0
Ophe	3	0	0
Ophi	3	0	3
Ophioct	3	0	3
Ostra	0	1	0
Ostre	0	3	0
Otho	0	0	0
Owen	0	3	0
Oxyd	0	3	3
Pagur	2	0	2
Palae	3	0	0
Pand	3	0	0
Panda	3	0	0
Pant	1	0	2
Parad	2	0	0
Param	2	0	2
Paran	2	0	1
Pari	2	0	2
Pecti	2	0	0
Pedi	0	3	0
Perf	0	2	2
Perk	0	3	0
Peta	0	3	0
Phae	0	3	0
Phas	0	2	0
Pher	0	3	1
Phia	0	3	0
Pholi	3	0	0
Pholo	2	0	3

Phor	0	3	0
Phot	1	3	2
Phti	2	0	2
Phyla	0	3	0
Phyld	2	0	1
Pilu	2	0	3
Pinn	0	0	1
Pisid	2	0	3
Pisin	3	0	0
Pist	0	3	0
Plag	0	3	0
Plat	0	0	3
Pleuc	0	3	0
Pleun	3	0	0
Plum	0	3	0
Poda	2	0	3
Podo	1	0	2
Poec	3	3	0
Polyca	0	3	0
Polyce	0	0	3
Polyci	2	2	3
Polyd	0	3	0
Polyg	2	1	0
Polynd	3	0	3
Polyne	0	0	0
Porc	3	0	2
Pore	0	3	0
Port	3	0	0
Prax	0	3	0
Pria	0	3	0
Proce	2	0	1
Procs	0	3	0
Pros	0	0	3
Prot	3	1	1
Psamc	2	0	3
Psamt	2	0	1
Pseud	2	0	1
Pseul	0	3	2
Pseur	2	0	2
Pseut	0	3	0
Puel	0	3	0
Pygo	0	3	0
Pyra	0	3	0
Rasp	0	3	0
Rept	0	0	0

Riss	0	0	3
Sab	0	3	0
Sabed	0	3	0
Saber	0	3	0
Sacc	1	0	0
Saga	0	3	0
Sagi	0	0	1
Scal	0	1	2
Schig	2	0	1
Schip	0	3	0
Schis	3	0	1
Schiv	0	3	0
Scle	0	0	3
Scol	1	3	2
Scolo	3	0	0
Scrua	0	3	0
Scruo	0	3	0
Semi	0	3	0
Serp	0	3	0
Spham	2	0	1
Sphap	0	0	0
Sphas	2	0	1
Spio	0	3	2
Spiop	0	3	2
Spiro	0	3	0
Steno	2	0	2
Stenu	2	0	2
Sthe	3	0	3
Stre	0	0	0
Subad	2	0	1
Syco	0	3	0
Sylld	2	0	1
Sylls	1	2	1
Sync	2	0	2
Tanap	2	0	2
Tanas	0	0	3
Telm	3	0	0
Tere	0	3	0
Terg	0	0	3
Thar	0	1	1
Thec	0	0	3
Thel	0	3	0
Thia	0	0	3
Torn	0	0	3
Trav	3	0	0

Trit	0	0	2
Tryp	2	0	2
Tryph	2	0	2
Tubu	0	3	0
Tubul	0	3	0
Turb	0	3	0
Unci	1	0	3
Upog	3	0	3
Urot	2	0	3
Urti	0	3	0
Verr	0	3	0
Vesi	0	3	0

Table C-12 Substrate traits table

Taxa	Biological	Gravel	Hard	Mud	Sand
Abie	2	1	3	0	0
Ablu	2	3	1	0	2
Acan	2	1	3	0	0
Ache	3	0	2	0	0
Acid	0	0	0	2	3
Acti	3	0	3	0	0
Adal	3	0	1	0	0
Aeoli	0	3	2	1	3
Aequ	0	3	0	0	2
Aete	3	0	2	0	0
Alcyd	3	1	2	0	0
Alcym	0	0	3	0	0
Alcyo	3	0	3	0	0
Amae	0	0	0	3	2
Amat	3	0	2	0	0
Ampe	0	3	1	3	3
Amphar	0	0	0	3	2
Amphib	3	0	3	0	0
Amphic	0	2	0	3	3
Amphil	2	3	2	1	2
Amphip	3	2	3	0	1
Amphur	0	3	3	3	3
Anap	2	3	1	3	3
Anom	3	1	3	0	0
Anop	3	0	2	0	0
Anth	3	0	3	0	0
Aoni	0	1	2	0	3
Aorid	3	1	3	1	1
Aphe	0	1	2	0	3
Aphr	0	1	0	3	2
Aply	0	0	3	0	0
Apse	3	3	3	3	3
Arac	1	0	2	0	0
Arca	1	1	3	0	0
Aric	0	0	0	3	3
Asc	0	0	3	0	0
Ascl	0	1	3	0	0
Asdil	3	0	3	1	0
Aspi	3	0	2	0	0
Ast	1	1	2	2	2
Asta	0	3	0	1	2
Atel	0	3	1	1	3

Athe	2	0	2	3	3
Axiu	0	0	0	2	2
Ba	1	0	3	0	0
Barn	0	0	3	0	0
Bath	0	3	0	1	3
Bice	0	0	3	0	0
Boug	2	0	2	0	0
Brac	3	0	3	0	0
Bran	0	3	0	0	1
Bucc	0	3	1	2	3
Busk	2	0	0	0	0
Caec	0	0	0	3	3
Calla	0	0	0	3	2
Calli	2	3	3	1	2
Callo	3	0	3	0	0
Callp	3	0	2	0	0
Calyc	3	0	2	0	0
Campa	3	0	3	0	0
Canc	0	3	3	2	3
Capit	0	0	0	3	3
Carc	0	1	1	1	1
Caul	0	3	0	0	3
CCa	3	1	2	0	0
Cell	3	0	3	0	0
Cellrel	3	0	3	0	0
Cera	0	0	0	2	2
Ceri	0	1	0	2	3
Chaep	0	0	0	3	3
Chaez	0	1	0	3	3
Chei	0	3	2	3	2
Chor	3	0	3	0	0
Cirr	3	0	0	3	3
Clio	2	0	3	0	0
Clym	0	0	0	1	3
Clyti	3	0	2	0	0
Conop	1	0	3	0	0
Cop	0	0	2	0	2
Coro	1	0	3	3	3
Corye	3	0	2	0	0
Coryt	3	0	3	0	0
Crang	0	1	0	2	3
Crepi	0	0	3	0	0
Cres	0	3	3	0	2
Crib	1	0	1	0	0
Crisa	3	0	3	0	0

Crisu	0	0	3	0	0
Cten	2	2	2	0	0
Cuma	0	0	0	3	3
Dend	0	2	3	0	0
Dendr	3	1	3	0	0
Diad	0	0	3	0	0
Dide	3	0	2	0	0
Diod	0	0	3	0	0
Dip	3	0	3	0	0
Disp	3	0	3	0	0
Dori	1	1	3	1	1
Doto	3	3	3	0	0
Dril	1	0	0	3	3
Dyop	0	0	0	3	1
Ebal	0	3	0	2	3
Echin	0	0	3	3	3
Echiu	0	1	0	2	2
Ectop	3	0	3	0	0
Edwa	3	3	0	3	3
Elect	3	0	3	0	0
Embl	3	3	3	0	0
Ephe	0	3	3	0	1
Epit	0	0	0	3	3
Erict	2	1	3	0	0
Eschl	2	0	2	0	0
Eschn	3	0	2	0	0
Eteo	0	0	0	3	3
Eual	0	3	3	3	3
Eubr	3	3	3	0	0
Eucl	0	3	0	1	3
Euden	0	1	3	0	0
Euhete	0	1	0	1	1
Eula	0	3	3	0	3
Eumid	0	3	0	3	3
Eune	0	1	1	3	2
Eupo	0	2	3	3	3
Eury	0	1	0	1	3
Eusp	0	1	0	1	3
Eusy	0	2	3	1	1
Exog	0	2	3	1	1
Fabu	0	0	0	2	2
Facel	3	0	0	0	0
Fili	1	1	2	1	1
Filo	0	0	3	0	0
Flab	0	3	2	3	1

Gala	3	3	3	3	3
Galat	0	0	0	2	3
Gammd	3	3	0	0	3
Gammp	3	1	2	0	0
Gatt	3	1	1	3	3
Gibb	3	1	3	0	0
Gita	1	3	0	2	3
Glyce	1	3	3	2	3
Glyci	0	3	1	2	3
Glycy	0	3	0	2	2
Gnath	3	0	3	0	0
Golf	0	3	0	2	3
Gonia	0	3	1	2	3
Gonir	3	0	0	0	0
Good	0	3	0	3	2
Gwyn	0	0	3	0	0
Gypt	0	0	0	0	0
Hagi	0	0	0	0	0
Hale	0	0	3	0	0
Haplo	3	0	2	0	0
Harm	3	3	3	2	3
Harp	0	2	0	1	3
Hart	0	0	3	0	0
Hesi	0	2	0	0	3
Heteb	3	0	1	0	0
Heten	3	1	3	0	0
Hinc	2	2	0	0	0
Hippa	3	0	3	0	0
Hippy	0	3	3	3	3
Holo	0	3	0	0	2
Hyas	0	1	3	3	3
Hydr	2	0	2	0	0
Hydra	3	0	3	0	0
Hype	3	0	0	0	0
Idot	3	1	2	1	3
Ione	3	0	0	0	0
Iph	3	1	2	0	0
Ischy	2	1	2	0	1
Isop	1	1	2	1	1
Janu	1	1	1	0	0
Jass	3	0	3	0	0
Jsm	0	3	3	0	1
Kell	0	1	3	3	1
Kirc	1	1	3	0	0
Kurt	0	3	0	2	3

Lagi	2	1	0	3	3
Lago	0	0	0	0	0
Lani	0	2	1	2	3
Laom	3	0	3	0	0
Laoni	0	3	0	2	3
Lepi	0	1	3	0	0
Lepidepecre	0	3	0	2	3
Leptr	0	3	0	0	2
Leptt	1	1	3	2	2
Leucs	0	0	3	0	0
Leuct	3	0	2	3	3
Limac	0	1	3	0	0
Lioca	0	3	0	2	3
Lipa	0	2	2	0	0
Lumb	2	0	2	3	3
Lysid	2	3	2	3	3
Lysin	0	2	2	2	2
Macr	3	3	0	3	3
Macro	0	2	3	0	0
Maer	0	2	0	0	3
Mage	0	1	0	2	3
Majo	0	2	3	1	3
Mald	2	2	0	3	3
Malm	2	2	2	2	2
Marp	0	3	3	3	3
Medi	0	0	0	3	3
Meli	0	2	2	2	2
Meto	0	2	0	0	3
Metr	0	1	3	0	0
Micrel	2	0	2	0	0
Microm	3	0	0	0	0
Micros	2	0	2	3	3
Microt	0	1	0	2	3
Micrth	2	2	2	2	2
Mima	1	0	3	0	0
Molg	0	1	3	3	3
Mya	0	2	0	2	3
Myria	2	1	3	2	2
Mys	0	3	3	0	1
Mysi	0	0	0	3	3
Myti	0	1	3	1	1
Neme	1	1	2	1	1
Neoa	0	0	0	2	3
Neog	1	1	1	1	1
Nepha	0	3	3	2	3

Nephy	0	1	0	2	3
Nered	0	1	1	3	2
Neres	0	3	3	1	2
Nicol	0	1	3	2	2
Nicom	0	0	0	3	3
Noem	0	0	0	0	0
Nole	3	0	3	0	0
Noth	1	0	0	3	3
Notom	0	0	0	3	3
Notot	0	0	0	3	0
Nucu	0	3	0	3	2
Nymph	3	0	2	0	0
Obel	0	0	3	0	0
Odon	3	2	3	0	1
Oligo	0	1	0	2	2
Onch	2	1	3	0	0
Onco	0	0	0	0	0
Ophe	0	1	0	1	3
Ophi	0	2	0	3	3
Ophioct	0	0	0	2	3
Ostra	0	0	0	0	0
Ostre	0	1	3	1	0
Otho	0	0	0	0	0
Owen	0	0	0	2	3
Oxyd	0	0	0	2	2
Pagur	3	3	3	3	3
Palae	1	1	2	1	1
Pand	0	2	0	2	2
Panda	0	3	0	3	3
Pant	1	1	2	1	1
Parad	0	0	0	3	3
Param	0	2	0	1	3
Paran	0	2	2	3	3
Pari	0	3	0	2	2
Pecti	0	3	0	3	2
Pedi	2	0	3	0	0
Perf	1	0	3	0	0
Perk	0	0	3	0	0
Peta	0	0	0	3	3
Phae	0	2	3	0	0
Phas	2	0	0	3	3
Pher	0	1	1	3	2
Phia	2	0	2	0	0
Pholi	2	1	2	1	1
Pholo	0	3	1	1	3

Phor	0	0	3	0	0
Phot	0	0	0	2	3
Phti	3	2	2	1	1
Phyla	0	0	0	0	0
Phyld	0	1	3	3	3
Pilu	0	1	3	0	1
Pinn	3	0	0	0	0
Pisid	0	1	3	1	1
Pisin	0	2	1	2	3
Pist	0	3	0	3	3
Plag	3	0	3	0	0
Plat	0	1	1	1	1
Pleuc	3	0	0	0	0
Pleun	0	1	2	1	1
Plum	3	0	3	0	0
Poda	2	2	2	2	2
Podo	2	2	0	2	2
Poec	0	2	1	2	3
Polyca	0	2	3	2	0
Polyce	3	0	0	0	0
Polyci	0	0	2	2	3
Polyd	3	2	3	0	0
Polyg	0	3	0	0	3
Polynd	2	2	2	2	2
Polyne	0	0	0	0	0
Porc	0	2	2	1	1
Pore	0	0	3	0	0
Port	0	2	2	2	2
Prax	2	2	0	3	3
Pria	0	0	0	3	1
Proce	2	1	3	2	2
Procs	2	0	1	0	0
Pros	2	2	2	2	2
Prot	0	2	3	3	3
Psamc	0	3	3	0	1
Psamt	2	2	2	2	2
Pseud	0	3	3	0	3
Pseul	0	0	3	0	0
Pseur	3	1	2	0	0
Pseut	0	2	3	0	0
Puel	3	0	3	0	0
Pygo	0	0	3	3	0
Pyra	3	0	0	0	0
Rasp	0	0	3	0	0
Rept	0	0	0	0	0

Riss	3	1	3	3	3
Sab	0	2	0	3	3
Sabed	2	2	2	2	2
Saber	0	2	3	0	0
Sacc	0	2	0	0	3
Saga	3	3	3	3	3
Sagi	0	0	0	0	0
Scal	0	0	0	3	3
Schig	0	3	1	3	3
Schip	3	0	3	0	0
Schis	0	0	0	0	0
Schiv	3	0	3	0	0
Scle	0	0	0	3	0
Scol	0	0	2	2	3
Scolo	0	2	0	3	3
Scrua	3	0	3	0	0
Scruo	3	0	3	0	0
Semi	1	0	3	0	0
Serp	0	0	3	0	0
Spham	0	3	3	0	0
Sphap	0	0	0	0	0
Sphas	0	3	0	3	2
Spio	0	1	0	1	3
Spiop	0	1	0	1	3
Spiro	0	0	3	0	0
Steno	2	1	2	0	2
Stenu	0	1	1	1	3
Sthe	0	1	0	3	3
Stre	0	0	0	0	0
Subad	0	0	3	0	0
Syco	3	0	3	0	0
Sylld	2	2	2	2	2
Sylls	0	3	3	0	1
Sync	0	3	0	1	3
Tanap	0	3	0	2	3
Tanas	0	0	0	0	3
Telm	0	0	3	0	0
Tere	1	1	2	1	1
Terg	3	1	3	0	0
Thar	3	0	0	3	3
Thec	3	0	0	0	0
Thel	0	3	2	3	3
Thia	0	1	0	1	3
Torn	0	3	3	0	2
Trav	0	0	0	1	3

Trit	2	0	0	1	1
Tryp	0	0	0	2	2
Tryph	0	2	0	2	3
Tubu	3	0	3	0	0
Tubul	3	0	3	0	0
Turb	3	0	3	0	0
Unci	0	3	3	2	0
Upog	0	1	0	3	3
Urot	0	3	1	1	3
Urti	0	1	3	0	0
Verr	1	0	3	0	0
Vesi	3	0	3	0	0

Appendix D R code for biological traits analysis

D.1 Cluster analysis (Chapter4.3.2.1)

```
#Import datasets for cluster analysis
Clbi <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\Cluster\\Cluster bioturbation.csv", row.names=1, header=TRUE)
Clsh <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\Cluster\\Cluster shape.csv", row.names=1, header=TRUE)
Clfc <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\Cluster\\Cluster fecundity.csv", row.names=1, header=TRUE)
Clfd <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\Cluster\\Cluster feed.csv", row.names=1, header=TRUE)
Clha <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\Cluster\\Cluster habitat.csv", row.names=1, header=TRUE)
Clde <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\Cluster\\Cluster development.csv", row.names=1, header=TRUE)
Cldu <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\Cluster\\Cluster duration.csv", row.names=1, header=TRUE)
Clsi <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\Cluster\\Cluster size.csv", row.names=1, header=TRUE)
Clsu <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\Cluster\\Cluster substrate.csv", row.names=1, header=TRUE)
Clm <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\Cluster\\Cluster mobility.csv", row.names=1, header=TRUE)
# Draw graphics in a 2 by 2 grid
par(mfrow=c(2,2))
# Cluster analysis of bioturbation
Clbi1.2 <- t(Clbi)
Clbi2 <- vegdist(Clbi1.2, method="bray", binary=FALSE)
Clbi3 <- hclust(Clbi2, method="ward.D")
Clbi4 <- color_branches(Clbi3, k=2)
color_labels(Clbi4, k=2) %>% plot(horiz=TRUE)
title("Bioturbation")
# Cluster analysis of body shape
Clsh2 <- vegdist(Clsh1.2, method="bray", binary=FALSE)
Clsh3 <- hclust(Clsh2, method="ward.D")
Clsh4 <- color_branches(Clsh3, k=2)
color_labels(Clsh4, k=2) %>% plot(horiz=TRUE)
title("Body shape")
# Cluster analysis of fecundity
Clfc1.2 <- t(Clfc)
Clfc2 <- vegdist(Clfc1.2, method="bray", binary=FALSE)
Clfc3 <- hclust(Clfc2, method="ward.D")
Clfc4 <- color_branches(Clfc3, k=2)
color_labels(Clfc4, k=2) %>% plot(horiz=TRUE)
title("Fecundity")
# Cluster analysis of feeding mode
Clfd1.2 <- t(Clfd)
Clfd2 <- vegdist(Clfd1.2, method="bray", binary=FALSE)
```

```
Clfd3 <- hclust(Clfd2, method="ward.D")
Clfd4 <- color_branches(Clfd3, k=2)
color_labels(Clfd4, k=2) %>% plot(horiz=TRUE)
title("Feeding mode")
# Cluster analysis of habitat engineering
Clha1.2 <- t(Clha)
Clha2 <- vegdist(Clha1.2, method="bray", binary=FALSE)
Clha3 <- hclust(Clha2, method="ward.D")
Clha4 <- color_branches(Clha3, k=2)
color_labels(Clha4, k=2) %>% plot(horiz=TRUE)
title("Habitat engineers")
# Cluster analysis of larval development
Clde.2 <- t(Clde)
Clde2 <- vegdist(Clde.2, method="bray", binary=FALSE)
Clde3 <- hclust(Clde2, method="ward.D")
Clde4 <- color_branches(Clde3, k=2)
color_labels(Clde4, k=2) %>% plot(horiz=TRUE)
title("Larval development")
# Cluster analysis of larval duration
Cldu1.2 <- t(Cldu)
Cldu2 <- vegdist(Cldu1.2, method="bray", binary=FALSE)
Cldu3 <- hclust(Cldu2, method="ward.D")
Cldu4 <- color_branches(Cldu3, k=2)
color_labels(Cldu4, k=2) %>% plot(horiz=TRUE)
title("Larval duration")
# Cluster analysis of longevity
Cllo <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\Cluster\\Cluster longevity.csv", row.names=1, header=TRUE)
Cllo1.2 <- t(Cllo)
Cllo2 <- vegdist(Cllo1.2, method="bray", binary=FALSE)
Cllo3 <- hclust(Cllo2, method="ward.D")
Cllo4 <- color_branches(Cllo3, k=2)
color_labels(Cllo4, k=2) %>% plot(horiz=TRUE)
title("longevity")
# Cluster analysis of maximum adult size
Clsi1.2 <- t(Clsi)
Clsi2 <- vegdist(Clsi1.2, method="bray", binary=FALSE)
Clsi3 <- hclust(Clsi2, method="ward.D")
Clsi4 <- color_branches(Clsi3, k=2)
color_labels(Clsi4, k=2) %>% plot(horiz=TRUE)
title("Max adult size")
# Cluster analysis of preferred substrate
Clsu1.2 <- t(Clsu)
Clsu2 <- vegdist(Clsu1.2, method="bray", binary=FALSE)
Clsu3 <- hclust(Clsu2, method="ward.D")
Clsu4 <- color_branches(Clsu3, k=2)
color_labels(Clsu4, k=2) %>% plot(horiz=TRUE)
title("Preferred substrate")
```

```
# Cluster analysis of strategies for displacement
Clm1.2 <- t(Clm)
Clm2 <- vegdist(Clm1.2, method="bray", binary=FALSE)
Clm3 <- hclust(Clm2, method="ward.D")
Clm4 <- color_branches(Clm3, k=2)
color_labels(Clm4, k=2) %>% plot(horiz=TRUE)
title("Strategies for displacement")
```

D.2 Co-inertia analysis (Chapter 4.3.2.2)

```
#Import group A-D taxa abundance data
TMA <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\A\\TAMA.csv", row.names=1, header=TRUE)
TMB <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\B\\TAMB.csv", row.names=1, header=TRUE)
TMC <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\C\\TAMC.csv", row.names=1, header=TRUE)
TMD <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\D\\TAMD.csv", row.names=1, header=TRUE)
#Log+1 transform group A-D taxa abundance data
TMLA <- log(TMA+1)
TMLB <- log(TMB+1)
TMLC <- log(TMC+1)
TMLD <- log(TMD+1)
#Import group A-D biological traits data
#Bioturbation
Bioa <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\A\\Bioturbation A.csv", row.names=1, header=TRUE)
Biob <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\B\\Bioturbation B.csv", row.names=1, header=TRUE)
BioC <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\C\\Bioturbation C.csv", row.names=1, header=TRUE)
Biod <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\D\\Bioturbation D.csv", row.names=1, header=TRUE)
#Body shape
BoSha <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\A\\Shape A.csv", row.names=1, header=TRUE)
BoShb <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\B\\Shape B.csv", row.names=1, header=TRUE)
BoShC <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\C\\Shape C.csv", row.names=1, header=TRUE)
BoShd <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\D\\Shape D.csv", row.names=1, header=TRUE)
#Fecundity
Feca <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\A\\Fecundity A.csv", row.names=1, header=TRUE)
Fecb <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\B\\Fecundity B.csv", row.names=1, header=TRUE)
```

```
Fecc <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\C\\Fecundity C.csv", row.names=1, header=TRUE)
Fecd <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\D\\Fecundity D.csv", row.names=1, header=TRUE)
#Feeding mode
FMa <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\A\\Feed A.csv", row.names=1, header=TRUE)
FMb <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\B\\Feed B.csv", row.names=1, header=TRUE)
FMc <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\C\\Feed C.csv", row.names=1, header=TRUE)
FMd <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\D\\Feed D.csv", row.names=1, header=TRUE)
#Habitat engineering
HEnga <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\A\\Habitat A.csv", row.names=1, header=TRUE)
HEngb <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\B\\Habitat B.csv", row.names=1, header=TRUE)
HEngc <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\C\\Habitat C.csv", row.names=1, header=TRUE)
HEngd <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\D\\Habitat D.csv", row.names=1, header=TRUE)
#Larval development
LDeva <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\A\\Development A.csv", row.names=1, header=TRUE)
LDevb <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\B\\Development B.csv", row.names=1, header=TRUE)
LDevc <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\C\\Development C.csv", row.names=1, header=TRUE)
LDevd <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\D\\Development D.csv", row.names=1, header=TRUE)
#Larval duration
LDura <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\A\\Duration A.csv", row.names=1, header=TRUE)
LDurb <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\B\\Duration B.csv", row.names=1, header=TRUE)
LDurc <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\C\\Duration C.csv", row.names=1, header=TRUE)
LDurd <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\D\\Duration D.csv", row.names=1, header=TRUE)
#Longevity
Longa <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\A\\Longevity A.csv", row.names=1, header=TRUE)
Longb <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\B\\Longevity B.csv", row.names=1, header=TRUE)
Longc <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits analysis\\BTA\\C\\Longevity C.csv", row.names=1, header=TRUE)
```

```
Longd <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\D\\Longevity D.csv", row.names=1, header=TRUE)
#Maximum adult size
Maxa <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\A\\Size A.csv", row.names=1, header=TRUE)
Maxb <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\B\\Size B.csv", row.names=1, header=TRUE)
Maxc <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\C\\Size C.csv", row.names=1, header=TRUE)
Maxd <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\D\\Size D.csv", row.names=1, header=TRUE)
#Preferred substrate
Suba <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\A\\Substrate A.csv", row.names=1, header=TRUE)
Subb <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\B\\Substrate B.csv", row.names=1, header=TRUE)
Subc <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\C\\Substrate C.csv", row.names=1, header=TRUE)
Subd <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\D\\Substrate D.csv", row.names=1, header=TRUE)
#Strategies for displacement
Moba <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\A\\Mobility A.csv", row.names=1, header=TRUE)
Mobb <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\B\\Mobility B.csv", row.names=1, header=TRUE)
Mobc <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\C\\Mobility C.csv", row.names=1, header=TRUE)
Mobd <- read.csv("C:\\Users\\Paul\\Documents\\Cranfield\\4. Biological traits
analysis\\BTA\\D\\Mobility D.csv", row.names=1, header=TRUE)
#Coinertia analysis A-D
#Group A bioturbation
Col.blocks.Bioa<- prep.fuzzy.var(Bioa, 6) #Define col.blocks (vector containing number of
categories for each fuzzy trait variable)
fpcaBioa <- dudi.fpca(Col.blocks.Bioa, scan=FALSE) #fuzzy pca for col.blocks
pcaBioa <- dudi.pca(TMLA, scale=TRUE, scan=FALSE) #pca abundance data
cor(fpcaBioa$li, pcaBioa$li)
CoinBioa <- coinertia(fpcaBioa, pcaBioa, scan=FALSE)
CoinBioa
BturbA <- plot(CoinBioa, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
BturbA2 <- plot(CoinBioa, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
BturbA2$XYmatch
insert(BturbA$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(BturbA$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(BturbA$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group A body shape
Col.blocks.BoSha<- prep.fuzzy.var(BoSha, 5)
fpcaBoSha <- dudi.fpca(Col.blocks.BoSha, scan=FALSE)
pcaBoSha <- dudi.pca(TMLA, scale=TRUE, scan=FALSE)
```

```
cor(fpcaBoSha$li, pcaBoSha$li)
CoinBoSha <- coinertia(fpcaBoSha, pcaBoSha, scan=FALSE)
CoinBoSha
BshapA <- plot(CoinBoSha, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
BshapA2 <- plot(CoinBoSha, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
BshapA2$XYmatch
insert(BshapA$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(BshapA$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(BshapA$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group A fecundity
Col.blocks.Feca<- prep.fuzzy.var(Feca, 4)
fpcaFeca <- dudi.fpca(Col.blocks.Feca, scan=FALSE)
pcaFeca <- dudi.pca(TMLA, scale=TRUE, scan=FALSE)
cor(fpcaFeca$li, pcaFeca$li)
CoinFeca <- coinertia(fpcaFeca, pcaFeca, scan=FALSE)
CoinFeca
FecunA <- plot(CoinFeca, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
FecunA2 <- plot(CoinFeca, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
FecunA2$XYmatch
insert(FecunA$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(FecunA$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(FecunA$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group A feeding mode
Col.blocks.FMa<- prep.fuzzy.var(FMa, 6)
fpcaFMa <- dudi.fpca(Col.blocks.FMa, scan=FALSE)
pcaFMa <- dudi.pca(TMLA, scale=TRUE, scan=FALSE)
cor(fpcaFMa$li, pcaFMa$li)
CoinFMa <- coinertia(fpcaFMa, pcaFMa, scan=FALSE)
CoinFMa
FeedA <- plot(CoinFMa, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
Feed2A <- plot(CoinFMa, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
Feed2A$XYmatch
insert(FeedA$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(FeedA$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(FeedA$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group A habitat engineers
Col.blocks.HEnga<- prep.fuzzy.var(HEnga, 4)
fpcaHEnga <- dudi.fpca(Col.blocks.HEnga, scan=FALSE)
pcaHEnga <- dudi.pca(TMLA, scale=TRUE, scan=FALSE)
cor(fpcaHEnga$li, pcaHEnga$li)
CoinHEnga <- coinertia(fpcaHEnga, pcaHEnga, scan=FALSE)
CoinHEnga
HabA <- plot(CoinHEnga, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
HabA2 <- plot(CoinHEnga, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
HabA2$XYmatch
insert(HabA$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(HabA$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(HabA$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
```

```
# Group A larval development
Col.blocks.LDeva<- prep.fuzzy.var(LDeva, 3)
fpcaLDeva <- dudi.fpca(Col.blocks.LDeva, scan=FALSE)
pcaLDeva <- dudi.pca(TMLA, scale=TRUE, scan=FALSE)
cor(fpcaLDeva$li, pcaLDeva$li)
CoinLDeva <- coinertia(fpcaLDeva, pcaLDeva, scan=FALSE)
CoinLDeva
LarDeA <- plot(CoinLDeva, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
LarDeA2 <- plot(CoinLDeva, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
LarDeA2$XYmatch
insert(LarDeA$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(LarDeA$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(LarDeA$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group A larval duration
Col.blocks.LDura<- prep.fuzzy.var(LDura, 6)
fpcaLDura <- dudi.fpca(Col.blocks.LDura, scan=FALSE)
pcaLDura <- dudi.pca(TMLA, scale=TRUE, scan=FALSE)
cor(fpcaLDura$li, pcaLDura$li)
CoinLDura <- coinertia(fpcaLDura, pcaLDura, scan=FALSE)
CoinLDura
LarDuA <- plot(CoinLDura, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
LarDuA2 <- plot(CoinLDura, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
LarDuA2$XYmatch
insert(LarDuA$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(LarDuA$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(LarDuA$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group A longevity
Col.blocks.Longa<- prep.fuzzy.var(Longa, 4)
fpcaLonga <- dudi.fpca(Col.blocks.Longa, scan=FALSE)
pcaLonga <- dudi.pca(TMLA, scale=TRUE, scan=FALSE)
cor(fpcaLonga$li, pcaLonga$li)
CoinLonga <- coinertia(fpcaLonga, pcaLonga, scan=FALSE)
CoinLonga
LonA <- plot(CoinLonga, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
LonA2 <- plot(CoinLonga, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
LonA2$XYmatch
insert(LonA$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(LonA$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(LonA$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group A maximum size
Col.blocks.Maxa<- prep.fuzzy.var(Maxa, 4)
fpcaMaxa <- dudi.fpca(Col.blocks.Maxa, scan=FALSE)
pcaMaxa <- dudi.pca(TMLA, scale=TRUE, scan=FALSE)
cor(fpcaMaxa$li, pcaMaxa$li)
CoinMaxa <- coinertia(fpcaMaxa, pcaMaxa, scan=FALSE)
CoinMaxa
MaxA <- plot(CoinMaxa, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
MaxA2 <- plot(CoinMaxa, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
```

```
MaxA2$XYmatch
insert(MaxA$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(MaxA$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(MaxA$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group A preferred substrate
Col.blocks.Suba<- prep.fuzzy.var(Suba, 5)
fpcaSuba <- dudi.fpca(Col.blocks.Suba, scan=FALSE)
pcaSuba <- dudi.pca(TMLA, scale=TRUE, scan=FALSE)
cor(fpcaSuba$li, pcaSuba$li)
CoinSuba <- coinertia(fpcaSuba, pcaSuba, scan=FALSE)
CoinSuba
PreSuA <- plot(CoinSuba, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
PreSuA2 <- plot(CoinSuba, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
PreSuA2$XYmatch
insert(PreSuA$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(PreSuA$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(PreSuA$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group A strategies for displacement
Col.blocks.Moba<- prep.fuzzy.var(Moba, 3)
fpcaMoba <- dudi.fpca(Col.blocks.Moba, scan=FALSE)
pcaMoba <- dudi.pca(TMLA, scale=TRUE, scan=FALSE)
cor(fpcaMoba$li, pcaMoba$li)
CoinMoba <- coinertia(fpcaMoba, pcaMoba, scan=FALSE)
CoinMoba
StratDA <- plot(CoinMoba, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
StratDA2 <- plot(CoinMoba, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
StratDA2$XYmatch
insert(StratDA$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(StratDA$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(StratDA$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group B bioturbation
Col.blocks.Biob <- prep.fuzzy.var(Biob, 6)
fpcaBiob <- dudi.fpca(Col.blocks.Biob, scan=FALSE)
pcaBiob <- dudi.pca(TMLB, scale=TRUE, scan=FALSE)
cor(fpcaBiob$li, pcaBiob$li)
CoinBiob <- coinertia(fpcaBiob, pcaBiob, scan=FALSE)
CoinBiob
BturbB <- plot(CoinBiob, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
BturbB2 <- plot(CoinBiob, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
BturbB2$XYmatch
insert(BturbB$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(BturbB$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(BturbB$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group B body shape
Col.blocks.BoShb <- prep.fuzzy.var(BoShb, 5)
fpcaBoShb <- dudi.fpca(Col.blocks.BoShb, scan=FALSE)
pcaBoShb <- dudi.pca(TMLB, scale=TRUE, scan=FALSE)
cor(fpcaBoShb$li, pcaBoShb$li)
```

```
CoinBoShb <- coinertia(fpcaBoShb, pcaBoShb, scan=FALSE)
CoinBoShb
BshapB <- plot(CoinBoShb, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
BshapB2 <- plot(CoinBoShb, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
BshapB2$XYmatch
insert(BshapB$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(BshapB$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(BshapB$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group B fecundity
Col.blocks.Fecb <- prep.fuzzy.var(Fecb, 4)
fpcaFecb <- dudi.fpca(Col.blocks.Fecb, scan=FALSE)
pcaFecb <- dudi.pca(TMLB, scale=TRUE, scan=FALSE)
cor(fpcaFecb$li, pcaFecb$li)
CoinFecb <- coinertia(fpcaFecb, pcaFecb, scan=FALSE)
CoinFecb
FecunB <- plot(CoinFecb, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
FecunB2 <- plot(CoinFecb, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
FecunB2$XYmatch
insert(FecunB$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(FecunB$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(FecunB$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group B feeding mode
Col.blocks.FMb <- prep.fuzzy.var(FMb, 6)
fpcaFMb <- dudi.fpca(Col.blocks.FMb, scan=FALSE)
pcaFMb <- dudi.pca(TMLB, scale=TRUE, scan=FALSE)
cor(fpcaFMb$li, pcaFMb$li)
CoinFMb <- coinertia(fpcaFMb, pcaFMb, scan=FALSE)
CoinFMb
FeedB <- plot(CoinFMb, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
Feed2 <- plot(CoinFMb, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE, plines.col=1:4,
ppoints.col=1:4)
Feed2$XYmatch
insert(FeedB$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(FeedB$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(FeedB$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group B habitat engineers
Col.blocks.HEngb <- prep.fuzzy.var(HEngb, 4)
fpcaHEngb <- dudi.fpca(Col.blocks.HEngb, scan=FALSE)
pcaHEngb <- dudi.pca(TMLB, scale=TRUE, scan=FALSE)
cor(fpcaHEngb$li, pcaHEngb$li)
CoinHEngb <- coinertia(fpcaHEngb, pcaHEngb, scan=FALSE)
CoinHEngb
HabB <- plot(CoinHEngb, plab.cex=1.25, pgrid.draw=FALSE,  plot=FALSE)
HabB2 <- plot(CoinHEngb, plab.cex=FALSE, pgrid.draw=FALSE,  plot=FALSE)
HabB2$XYmatch
insert(HabB$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(HabB$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(HabB$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
```

```
# Group B larval development
Col.blocks.LDevb <- prep.fuzzy.var(LDevb, 3)
fpcaLDevb <- dudi.fpca(Col.blocks.LDevb, scan=FALSE)
pcaLDevb <- dudi.pca(TMLB, scale=TRUE, scan=FALSE)
cor(fpcaLDevb$li, pcaLDevb$li)
CoinLDevb <- coinertia(fpcaLDevb, pcaLDevb, scan=FALSE)
CoinLDevb
LarDeB <- plot(CoinLDevb, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
LarDeB2 <- plot(CoinLDevb, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
LarDeB2$XYmatch
insert(LarDeB$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(LarDeB$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(LarDeB$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group B larval duration
Col.blocks.LDurb <- prep.fuzzy.var(LDurb, 6)
fpcaLDurb <- dudi.fpca(Col.blocks.LDurb, scan=FALSE)
pcaLDurb <- dudi.pca(TMLB, scale=TRUE, scan=FALSE)
cor(fpcaLDurb$li, pcaLDurb$li)
CoinLDurb <- coinertia(fpcaLDurb, pcaLDurb, scan=FALSE)
CoinLDurb
LarDuB <- plot(CoinLDurb, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
LarDuB2 <- plot(CoinLDurb, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
LarDuB2$XYmatch
insert(LarDuB$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(LarDuB$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(LarDuB$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group B longevity
Col.blocks.Longb <- prep.fuzzy.var(Longb, 4)
fpcaLongb <- dudi.fpca(Col.blocks.Longb, scan=FALSE)
pcaLongb <- dudi.pca(TMLB, scale=TRUE, scan=FALSE)
cor(fpcaLongb$li, pcaLongb$li)
CoinLongb <- coinertia(fpcaLongb, pcaLongb, scan=FALSE)
CoinLongb
LonB <- plot(CoinLongb, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
LonB2 <- plot(CoinLongb, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
LonB2$XYmatch
insert(LonB$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(LonB$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(LonB$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group B maximum size
Col.blocks.Maxb <- prep.fuzzy.var(Maxb, 4)
fpcaMaxb <- dudi.fpca(Col.blocks.Maxb, scan=FALSE)
pcaMaxb <- dudi.pca(TMLB, scale=TRUE, scan=FALSE)
cor(fpcaMaxb$li, pcaMaxb$li)
CoinMaxb <- coinertia(fpcaMaxb, pcaMaxb, scan=FALSE)
CoinMaxb
MaxB <- plot(CoinMaxb, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
MaxB2 <- plot(CoinMaxb, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
```

```
MaxB2$XYmatch
insert(MaxB$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(MaxB$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(MaxB$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group B preferred substrate
Col.blocks.Subb <- prep.fuzzy.var(Subb, 5)
fpcaSubb <- dudi.fpca(Col.blocks.Subb, scan=FALSE)
pcaSubb <- dudi.pca(TMLB, scale=TRUE, scan=FALSE)
cor(fpcaSubb$li, pcaSubb$li)
CoinSubb <- coinertia(fpcaSubb, pcaSubb, scan=FALSE)
CoinSubb
PreSuB <- plot(CoinSubb, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
PreSuB2 <- plot(CoinSubb, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
PreSuB2$XYmatch
insert(PreSuB$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(PreSuB$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(PreSuB$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group B strategies for displacement
Col.blocks.Mobb <- prep.fuzzy.var(Mobb, 3)
fpcaMobb <- dudi.fpca(Col.blocks.Mobb, scan=FALSE)
pcaMobb <- dudi.pca(TMLB, scale=TRUE, scan=FALSE)
cor(fpcaMobb$li, pcaMobb$li)
CoinMobb <- coinertia(fpcaMobb, pcaMobb, scan=FALSE)
CoinMobb
StratDB <- plot(CoinMobb, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
StratDB2 <- plot(CoinMobb, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
StratDB2$XYmatch
insert(StratDB$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(StratDB$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(StratDB$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
# Group C Bioturbation
Col.blocks.Bioc<- prep.fuzzy.var(Bioc, 6)
fpcaBioc <- dudi.fpca(Col.blocks.Bioc, scan=FALSE) #fuzzy pca for col.blocks
pcaBioc <- dudi.pca(TMLC, scale=TRUE, scan=FALSE) #pca abundance data
cor(fpcaBioc$li, pcaBioc$li)
CoinBioc <- coinertia(fpcaBioc, pcaBioc, scan=FALSE)
CoinBioc
BturbC <- plot(CoinBioc, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
BturbC2 <- plot(CoinBioc, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
BturbC2$XYmatch
insert(BturbC$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(BturbC$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(BturbC$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group C body shape
Col.blocks.BoShc<- prep.fuzzy.var(BoShc, 5)
fpcaBoShc <- dudi.fpca(Col.blocks.BoShc, scan=FALSE)
pcaBoShc <- dudi.pca(TMLC, scale=TRUE, scan=FALSE)
cor(fpcaBoShc$li, pcaBoShc$li)
```

```
CoinBoShc <- coinertia(fpcaBoShc, pcaBoShc, scan=FALSE)
CoinBoShc
BshapC <- plot(CoinBoShc, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
BshapC2 <- plot(CoinBoShc, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
BshapC2$XYmatch
insert(BshapC$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(BshapC$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(BshapC$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group C fecundity
Col.blocks.Fecc<- prep.fuzzy.var(Fecc, 4)
fpcaFecc <- dudi.fpca(Col.blocks.Fecc, scan=FALSE)
pcaFecc <- dudi.pca(TMLC, scale=TRUE, scan=FALSE)
cor(fpcaFecc$li, pcaFecc$li)
CoinFecc <- coinertia(fpcaFecc, pcaFecc, scan=FALSE)
CoinFecc
FecunC <- plot(CoinFecc, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
FecunC2 <- plot(CoinFecc, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
FecunC2$XYmatch
insert(FecunC$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(FecunC$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(FecunC$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group C feeding mode
Col.blocks.FMc<- prep.fuzzy.var(FMc, 6)
fpcaFMc <- dudi.fpca(Col.blocks. FMc, scan=FALSE)
pcaFMc <- dudi.pca(TMLC, scale=TRUE, scan=FALSE)
cor(fpcaFMc$li, pcaFMc$li)
CoinFMc <- coinertia(fpcaFMc, pcaFMc, scan=FALSE)
CoinFMc
FeedC <- plot(CoinFMC, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
FeedC2 <- plot(CoinFMC, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
FeedC2$XYmatch
insert(FeedC$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(FeedC$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(FeedC$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group C habitat engineers
Col.blocks.HEngc<- prep.fuzzy.var(HEngc, 4)
fpcaHEngc <- dudi.fpca(Col.blocks.HEngc, scan=FALSE)
pcaHEngc <- dudi.pca(TMLC, scale=TRUE, scan=FALSE)
cor(fpcaHEngc$li, pcaHEngc$li)
CoinHEngc <- coinertia(fpcaHEngc, pcaHEngc, scan=FALSE)
CoinHEngc
HabC <- plot(CoinHEngc, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
HabC2 <- plot(CoinHEngc, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
HabC2$XYmatch
insert(HabC$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(HabC$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(HabC$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group C larval development
```

```
Col.blocks.LDevc<- prep.fuzzy.var(LDevc, 3)
fpcaLDevc <- dudi.fpca(Col.blocks.LDevc, scan=FALSE)
pcaLDevc <- dudi.pca(TMLC, scale=TRUE, scan=FALSE)
cor(fpcaLDevc$li, pcaLDevc$li)
CoinLDevc <- coinertia(fpcaLDevc, pcaLDevc, scan=FALSE)
CoinLDevc
LarDeC <- plot(CoinLDevc, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
LarDeC2 <- plot(CoinLDevc, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
LarDeC2$XYmatch
insert(LarDeC$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(LarDeC$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(LarDeC$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group C larval duration
Col.blocks.LDurc<- prep.fuzzy.var(LDurc, 6)
fpcaLDurc <- dudi.fpca(Col.blocks.LDurc, scan=FALSE)
pcaLDurc <- dudi.pca(TMLC, scale=TRUE, scan=FALSE)
cor(fpcaLDurc$li, pcaLDurc$li)
CoinLDurc <- coinertia(fpcaLDurc, pcaLDurc, scan=FALSE)
CoinLDurc
LarDuC <- plot(CoinLDurc, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
LarDuC2 <- plot(CoinLDurc, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
LarDuC2$XYmatch
insert(LarDuC$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(LarDuC$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(LarDuC$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group C longevity
Col.blocks.Longc<- prep.fuzzy.var(Longc, 4)
fpcaLongc <- dudi.fpca(Col.blocks.Longc, scan=FALSE)
pcaLongc <- dudi.pca(TMLC, scale=TRUE, scan=FALSE)
cor(fpcaLongc$li, pcaLongc$li)
CoinLongc <- coinertia(fpcaLongc, pcaLongc, scan=FALSE)
CoinLongc
LonC <- plot(CoinLongc, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
LonC2 <- plot(CoinLongc, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE, plines.col=1:4, ppoints.col=1:4)
LonC2$XYmatch
insert(LonC$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(LonC$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(LonC$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group C maximum size
Col.blocks.Maxc<- prep.fuzzy.var(Maxc, 4)
fpcaMaxc <- dudi.fpca(Col.blocks.Maxc, scan=FALSE)
pcaMaxc <- dudi.pca(TMLC, scale=TRUE, scan=FALSE)
cor(fpcaMaxc$li, pcaMaxc$li)
CoinMaxc <- coinertia(fpcaMaxc, pcaMaxc, scan=FALSE)
CoinMaxc
MaxC <- plot(CoinMaxc, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
MaxC2 <- plot(CoinMaxc, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
```

```
MaxC2$XYmatch
insert(MaxC$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(MaxC$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(MaxC$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group C preferred substrate
Col.blocks.Subc<- prep.fuzzy.var(Subc, 5)
fpcaSubc <- dudi.fpca(Col.blocks.Subc, scan=FALSE)
pcaSubc <- dudi.pca(TMLC, scale=TRUE, scan=FALSE)
cor(fpcaSubc$li, pcaSubc$li)
CoinSubc <- coinertia(fpcaSubc, pcaSubc, scan=FALSE)
CoinSubc
PreSuC <- plot(CoinSubc, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
PreSuC2 <- plot( CoinSubc, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
PreSuC2$XYmatch
insert(PreSuC$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(PreSuC$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(PreSuC$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group C Strategies for displacement
Col.blocks.MobC<- prep.fuzzy.var(MobC, 3)
fpcaMobC <- dudi.fpca(Col.blocks.MobC, scan=FALSE)
pcaMobC <- dudi.pca(TMLC, scale=TRUE, scan=FALSE)
cor(fpcaMobC$li, pcaMobC$li)
CoinMobC <- coinertia(fpcaMobC, pcaMobC, scan=FALSE)
CoinMobC
StratDC <- plot(CoinMobC, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
StratDC2 <- plot(CoinMobC, plab.cex=TRUE, pgrid.draw=FALSE, plot=FALSE)
StratDC2$XYmatch
insert(StratDC$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(StratDC$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(StratDC$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group D Bioturbation
Col.blocks.Biod<- prep.fuzzy.var(Biod, 6)
fpcaBiod <- dudi.fpca(Col.blocks.Biod, scan=FALSE)
pcaBiod <- dudi.pca(TMLD, scale=TRUE, scan=FALSE)
cor(fpcaBiod$li, pcaBiod$li)
CoinBiod <- coinertia(fpcaBiod, pcaBiod, scan=FALSE)
CoinBiod
BturbD <- plot(CoinBiod, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
BturbD2 <- plot(CoinBiod, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
BturbD2$XYmatch
insert(BturbD$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(BturbD$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(BturbD$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group D body shape
Col.blocks.BoShd<- prep.fuzzy.var(BoShd, 5)
fpcaBoShd <- dudi.fpca(Col.blocks.BoShd, scan=FALSE)
pcaBoShd <- dudi.pca(TMLD, scale=TRUE, scan=FALSE)
cor(fpcaBoShd$li, pcaBoShd$li)
```

```
CoinBoShd <- coinertia(fpcaBoShd, pcaBoShd, scan=FALSE)
BshapD <- plot(CoinBoShd, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
BshapD2 <-  plot(CoinBoShd, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
BshapD2$XYmatch
insert(BshapD$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(BshapD$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(BshapD$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group D fecundity
Col.blocks.Fecd<- prep.fuzzy.var(Fecd, 4)
fpcaFecd <- dudi.fpca(Col.blocks.Fecd, scan=FALSE)
pcaFecd <- dudi.pca(TMLD, scale=TRUE, scan=FALSE)
cor(fpcaFecd$li, pcaFecd$li)
CoinFecd <- coinertia(fpcaFecd, pcaFecd, scan=FALSE)
CoinFecd
FecunD <- plot(CoinFecd, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
FecunD2 <- plot(CoinFecd, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
FecunD2$XYmatch
insert(FecunD$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(FecunD$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(FecunD$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group D feeding mode
Col.blocks.FMd<- prep.fuzzy.var(FMd, 6)
fpcaFMd <- dudi.fpca(Col.blocks.FMd, scan=FALSE)
pcaFMd <- dudi.pca(TMLD, scale=TRUE, scan=FALSE)
cor(fpcaFMd$li, pcaFMd$li)
CoinFMd <- coinertia(fpcaFMd, pcaFMd, scan=FALSE)
CoinFMd
FeedD <- plot(CoinFMd, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
FeedD2 <- plot(CoinFMd, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
FeedD2$XYmatch
insert(FeedD$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(FeedD$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(FeedD$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group D habitat engineers
Col.blocks.HEngd<- prep.fuzzy.var(HEngd, 4)
fpcaHEngd <- dudi.fpca(Col.blocks.HEngd, scan=FALSE)
pcaHEngd <- dudi.pca(TMLD, scale=TRUE, scan=FALSE)
cor(fpcaHEngd$li, pcaHEngd$li)
CoinHEngd <- coinertia(fpcaHEngd, pcaHEngd, scan=FALSE)
CoinHEngd
HabD <- plot(CoinHEngd, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
HabD2 <- plot(CoinHEngd, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
HabD2$XYmatch
insert(HabD$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(HabD$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(HabD$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group D larval development
Col.blocks.LDevd<- prep.fuzzy.var(LDevD, 3)
```

```
fpcaLDevd <- dudi.fpca(Col.blocks.LDevD, scan=FALSE)
pcaLDevd <- dudi.pca(TMLD, scale=TRUE, scan=FALSE)
cor(fpcaLDevd$li, pcaLDevd$li)
CoinLDevd <- coinertia(fpcaLDevd, pcaLDevd, scan=FALSE)
CoinLDevd
LarDeD <- plot(CoinLDevd, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
LarDeD2 <- plot(CoinLDevd, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
LarDeD2$XYmatch
insert(LarDeD$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(LarDeD$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(LarDeD$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group D larval duration
Col.blocks.LDurd<- prep.fuzzy.var(LDurd, 6)
fpcaLDurd <- dudi.fpca(Col.blocks.LDurd, scan=FALSE)
pcaLDurd <- dudi.pca(TMLD, scale=TRUE, scan=FALSE)
cor(fpcaLDurd$li, pcaLDurd$li)
CoinLDurd <- coinertia(fpcaLDurd, pcaLDurd, scan=FALSE)
CoinLDurd
LarDuD <- plot(CoinLDurd, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
Lar2 <- plot(CoinLDurd, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
Lar2$XYmatch
insert(LarDuD$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(LarDuD$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(LarDuD$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group D longevity
Col.blocks.Longd<- prep.fuzzy.var(Longd, 4)
fpcaLongd <- dudi.fpca(Col.blocks.Longd, scan=FALSE)
pcaLongd <- dudi.pca(TMLD, scale=TRUE, scan=FALSE)
cor(fpcaLongd$li, pcaLongd$li)
CoinLongd <- coinertia(fpcaLongd, pcaLongd, scan=FALSE)
CoinLongd
LonD <- plot(CoinLongd, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
LonD2 <- plot(CoinLongd, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
LonD2$XYmatch
insert(LonD$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(LonD$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(LonD$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group D maximum size
Col.blocks.Maxd<- prep.fuzzy.var(Maxd, 4)
fpcaMaxd <- dudi.fpca(Col.blocks.Maxd, scan=FALSE)
pcaMaxd <- dudi.pca(TMLD, scale=TRUE, scan=FALSE)
cor(fpcaMaxd$li, pcaMaxd$li)
CoinMaxd <- coinertia(fpcaMaxd, pcaMaxd, scan=FALSE)
CoinMaxd
MaxD <- plot(CoinMaxd, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
MaxD2 <- plot(CoinMaxd, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
MaxD2$XYmatch
insert(MaxD$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
```

```
insert(MaxD$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(MaxD$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group D preferred substrate
Col.blocks.Subd<- prep.fuzzy.var(Subd, 5)
fpcaSubd <- dudi.fpca(Col.blocks.Subd, scan=FALSE)
pcaSubd <- dudi.pca(TMLD, scale=TRUE, scan=FALSE)
cor(fpcaSubd$li, pcaSubd$li)
CoinSubd <- coinertia(fpcaSubd, pcaSubd, scan=FALSE)
CoinSubd
PreSuD <- plot(CoinSubd, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
PreSuD2 <- plot(CoinSubd, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
PreSuD2$XYmatch
insert(PreSuD$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(PreSuD$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(PreSuD$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
#Group D strategies for displacement
Col.blocks.Mobd<- prep.fuzzy.var(Mobd, 3)
fpcaMobd <- dudi.fpca(Col.blocks.Mobd, scan=FALSE)
pcaMobd <- dudi.pca(TMLD, scale=TRUE, scan=FALSE)
cor(fpcaMobd$li, pcaMobd$li)
CoinMobd <- coinertia(fpcaMobd, pcaMobd, scan=FALSE)
CoinMobd
StratDD <- plot(CoinMobd, plab.cex=1.25, pgrid.draw=FALSE, plot=FALSE)
StratDD2 <- plot(CoinMobd, plab.cex=FALSE, pgrid.draw=FALSE, plot=FALSE)
StratDD2$XYmatch
insert(StratDD$Yloadings, posi="topright", ratio=0.35, inset=c(0.07, -0.001))
insert(StratDD$Xloadings, posi="bottomright", ratio=0.35, inset=c(0.07, 0.29))
insert(StratDD$eig, posi="bottomright", ratio=0.2, inset=c(-0.08, 0.08))
```

Appendix E Co-inertia analysis figures (Chapter 4.3.2.2)

Co-relationships presented in the following graphics were non-significant based on the monte-carlo test (*P* <0.05).

E.1 Group A

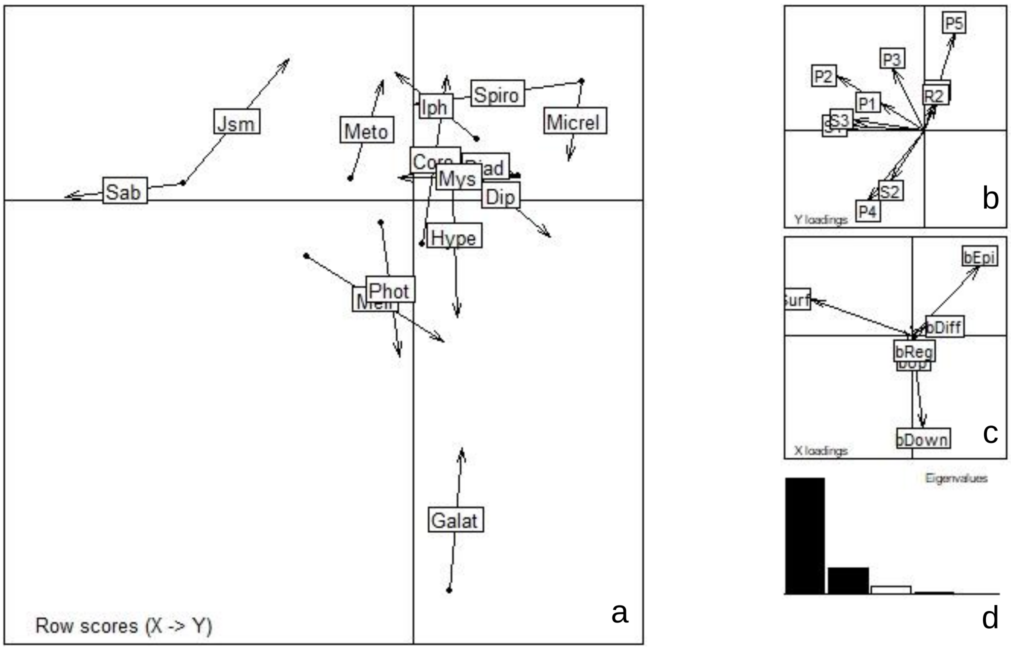

Figure E-1 CIA of bioturbation for group A. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

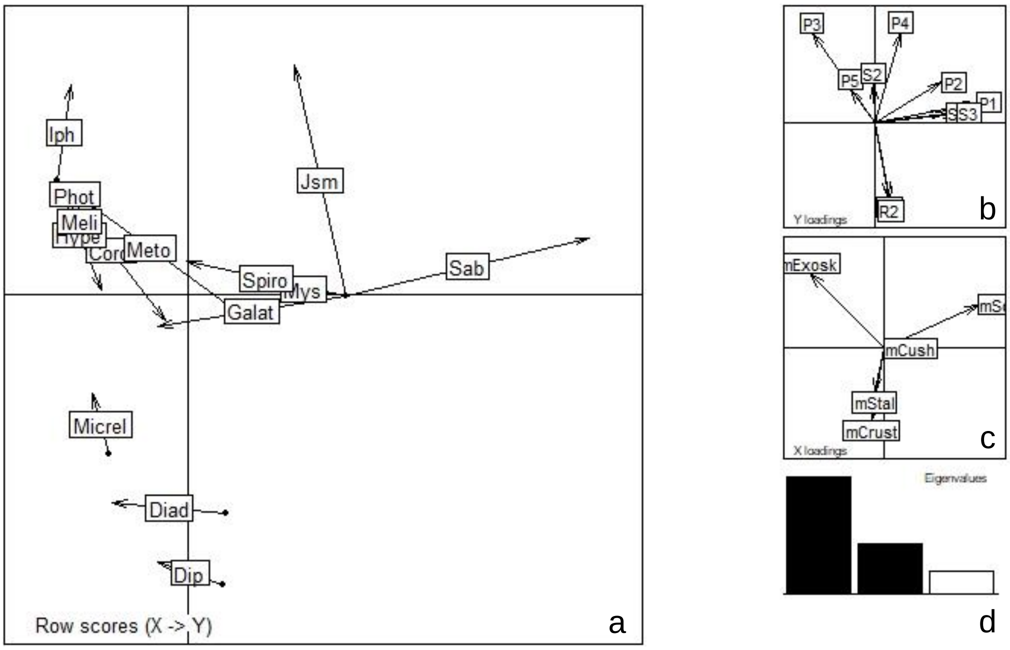

Figure E-2 CIA of body shape for group A. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

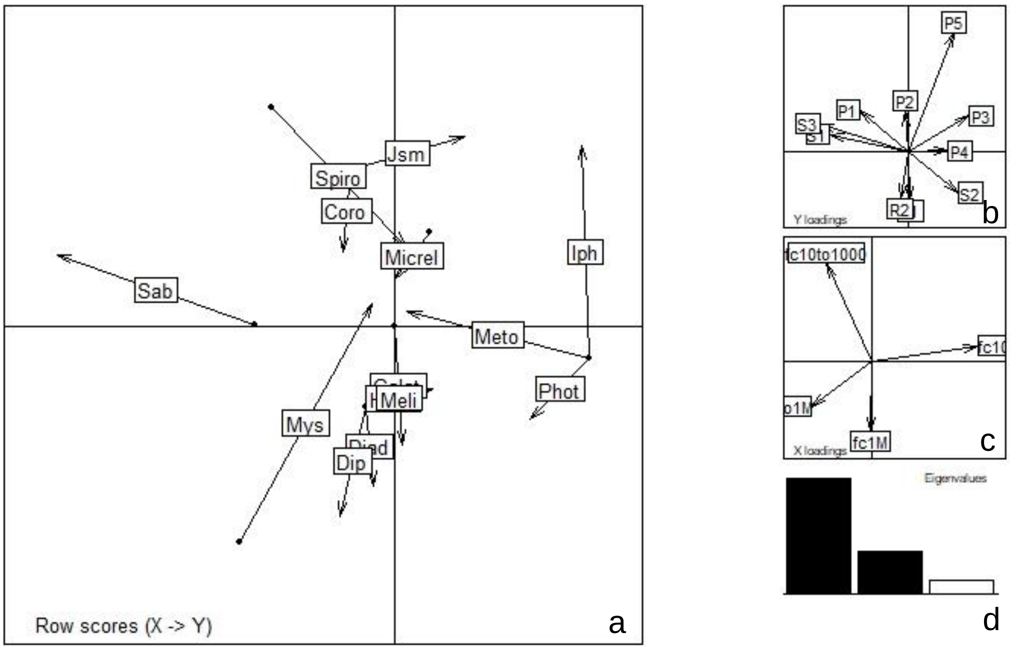

Figure E-3 CIA of fecundity for group A. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

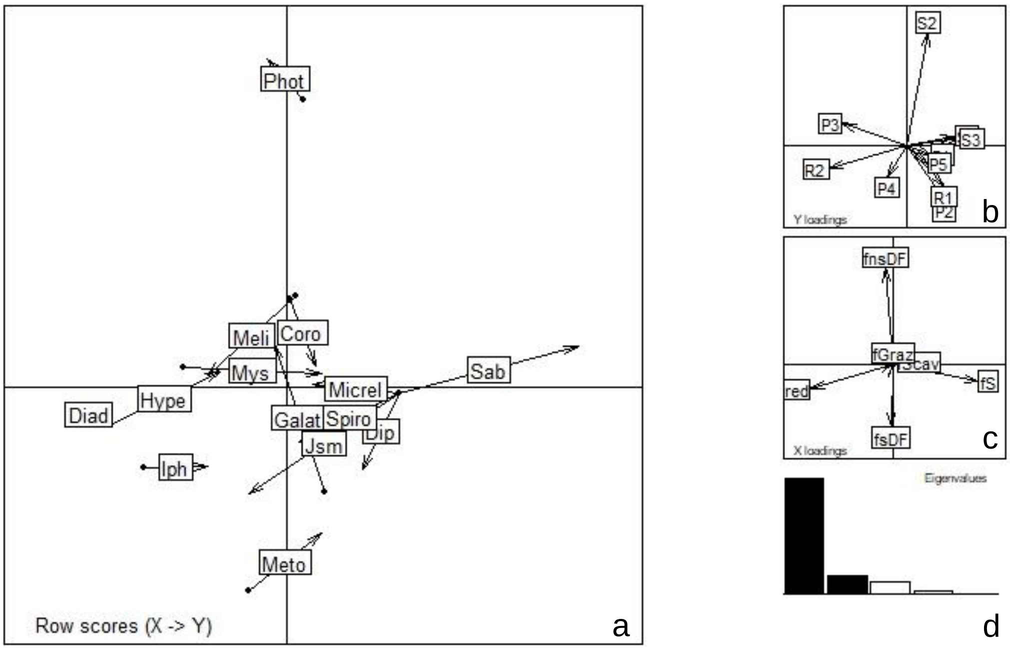

Figure E-4 CIA of feeding mode for group A. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

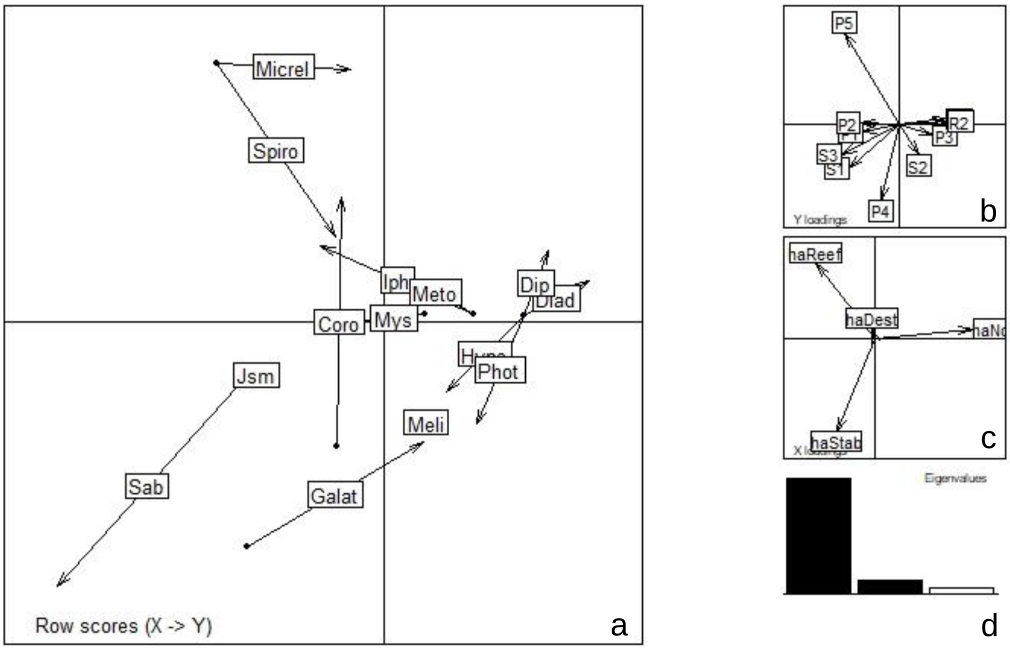

Figure E-5 CIA of habitat engineering for group A. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

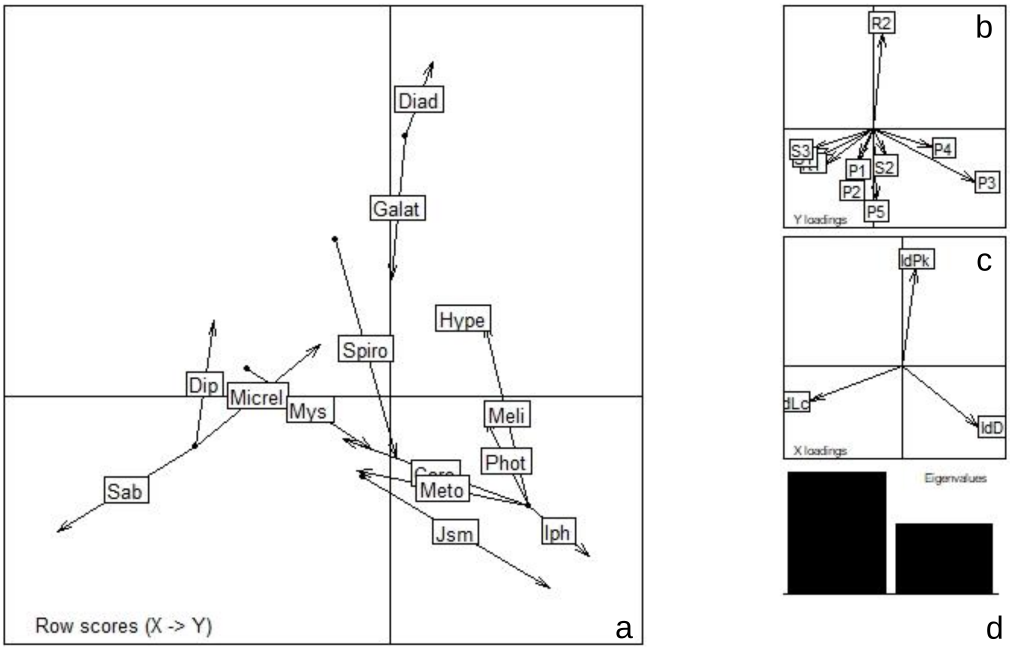

Figure E-6 CIA of larval development for group A. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

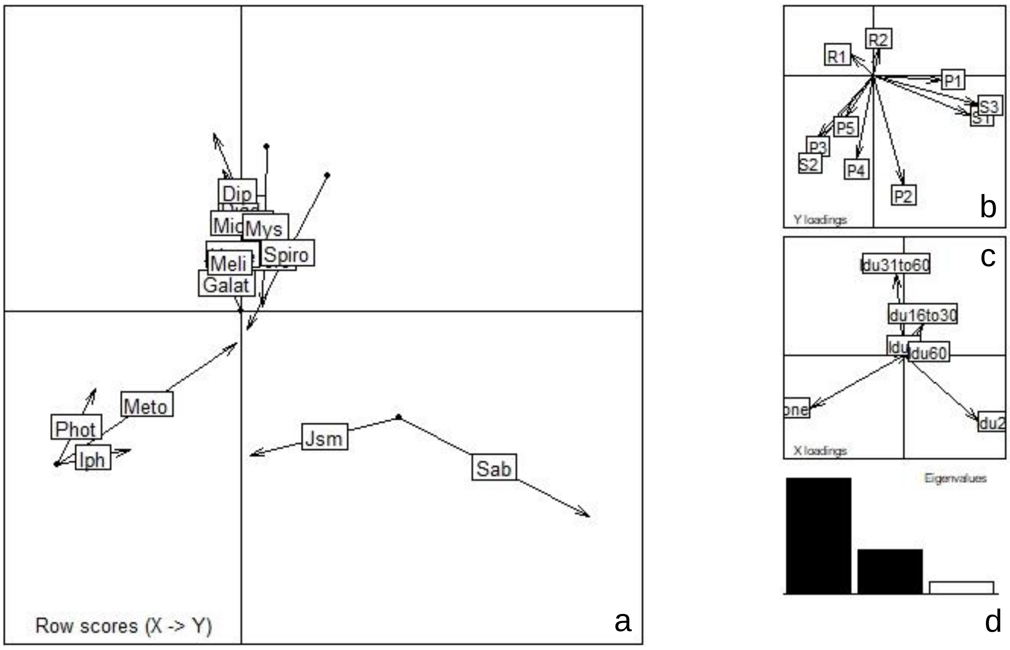

Figure E-7 CIA of larval duration for group A. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

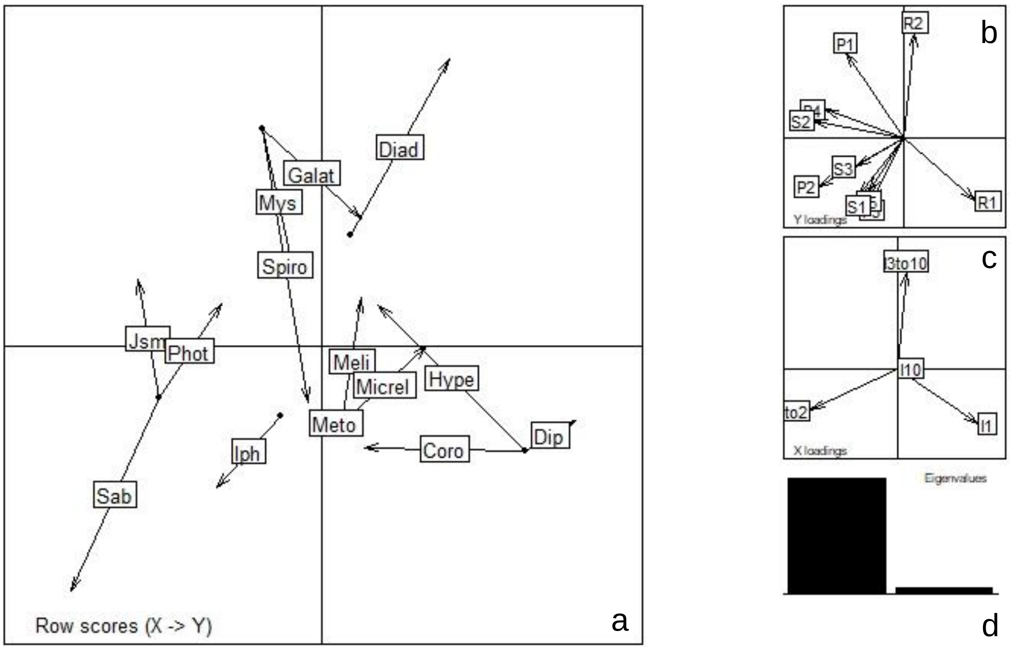

Figure E-8 CIA of longevity for group A. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

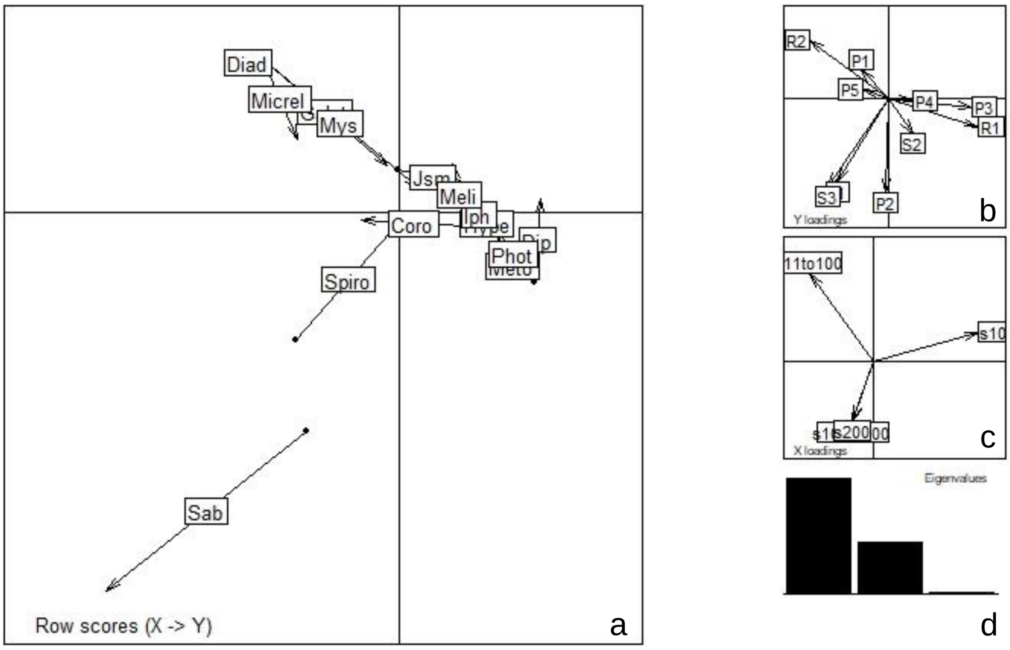

Figure E-9 CIA of maximum adult size (length or width) for group A. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

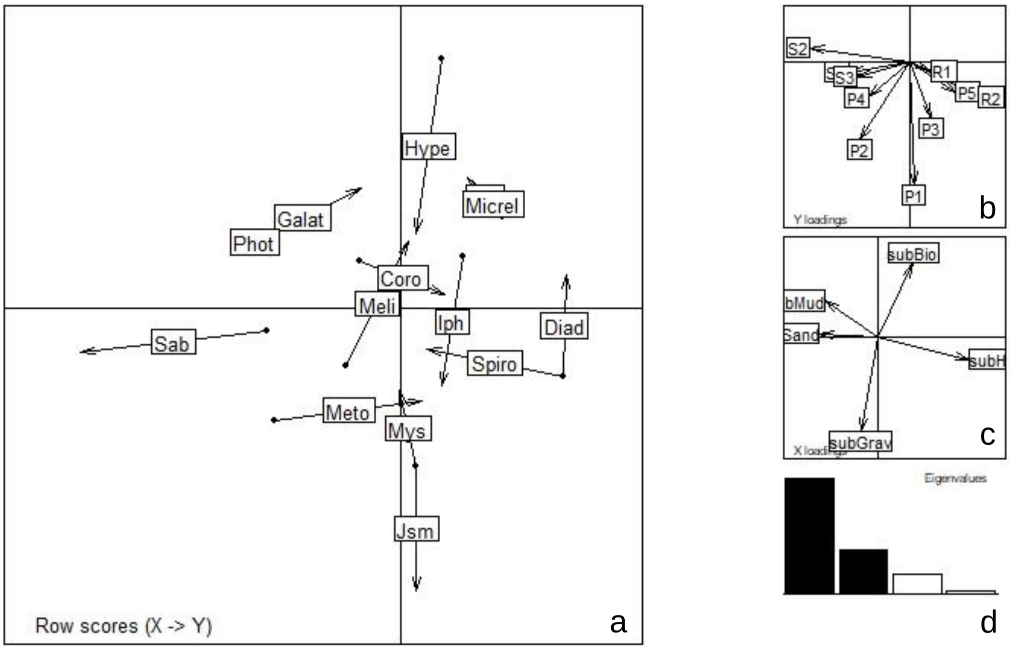

Figure E-10 CIA of preferred substrate for group A. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

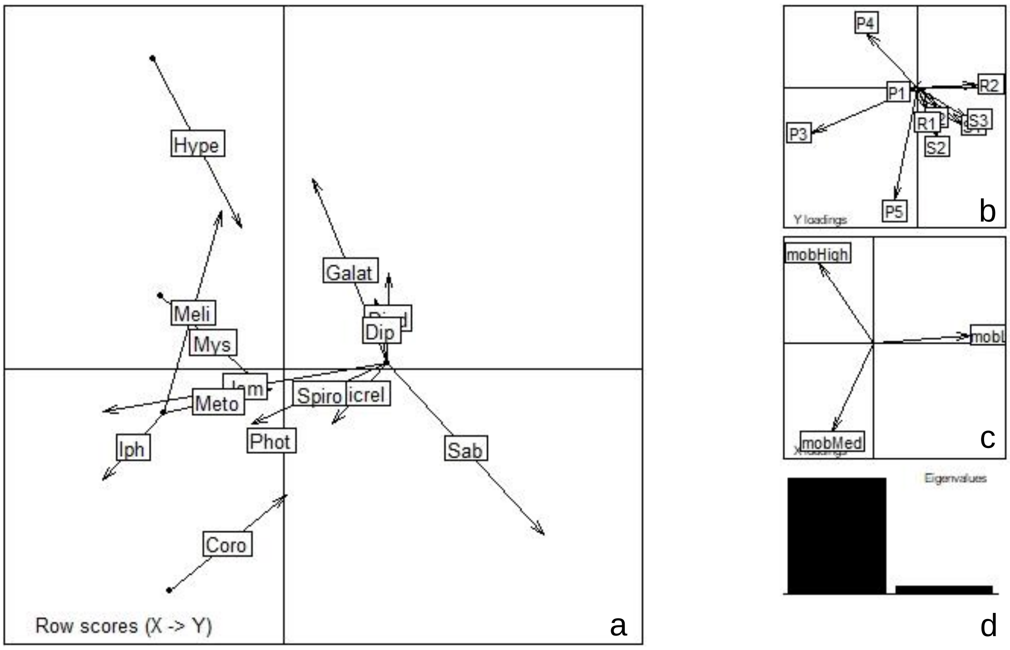

Figure E-11 CIA of strategies for displacement for group A. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

E.2 Group B

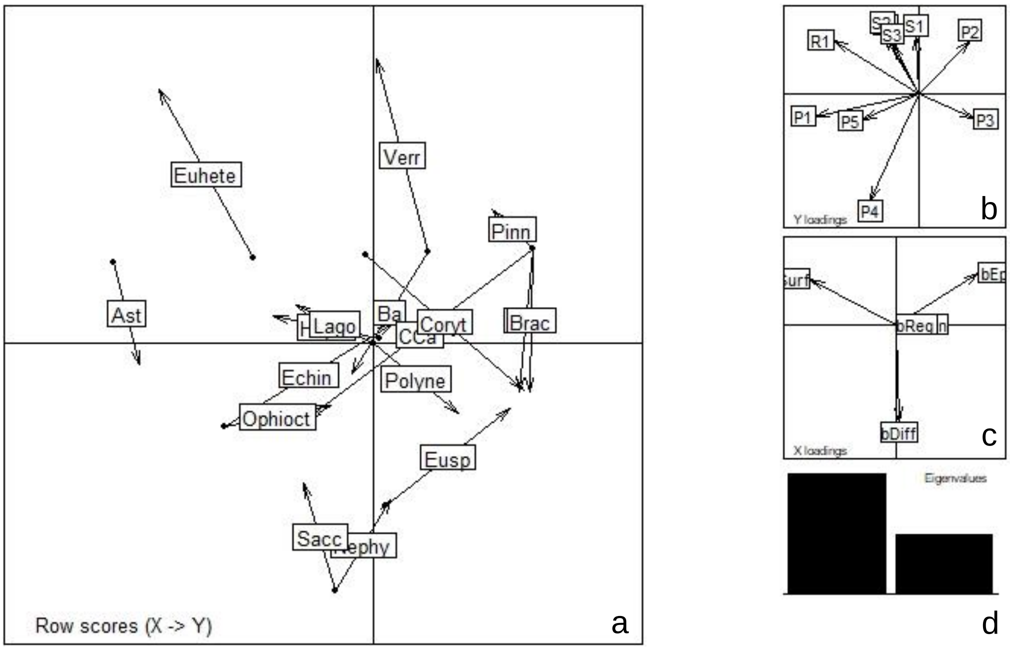

Figure E-12 CIA of bioturbation for group B. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

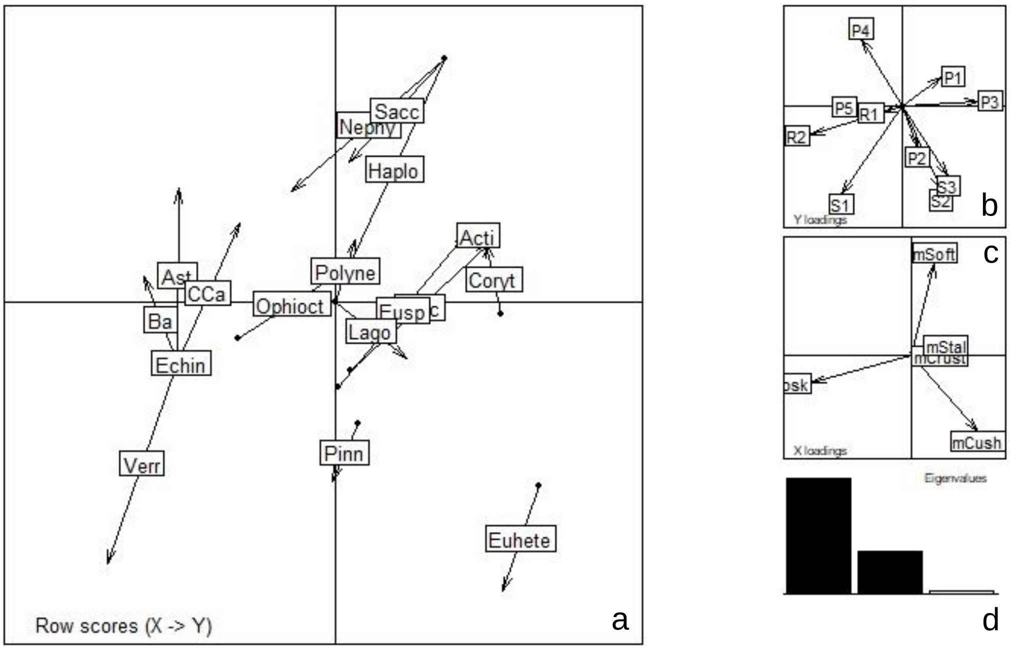

Figure E-13 CIA of body shape for group B. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

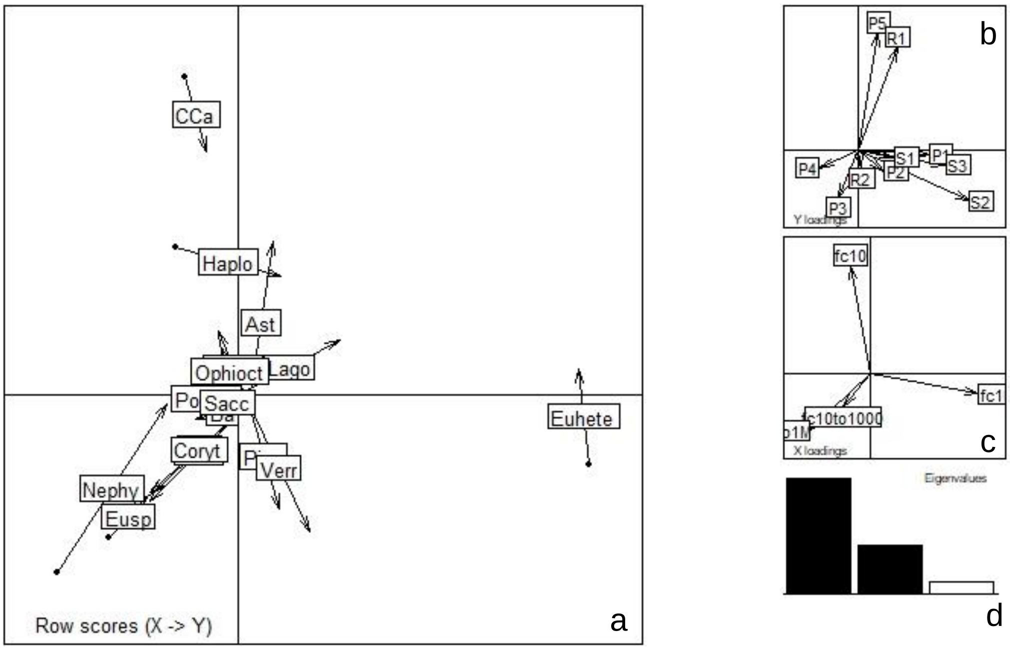

Figure E-14 CIA of fecundity for group B. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

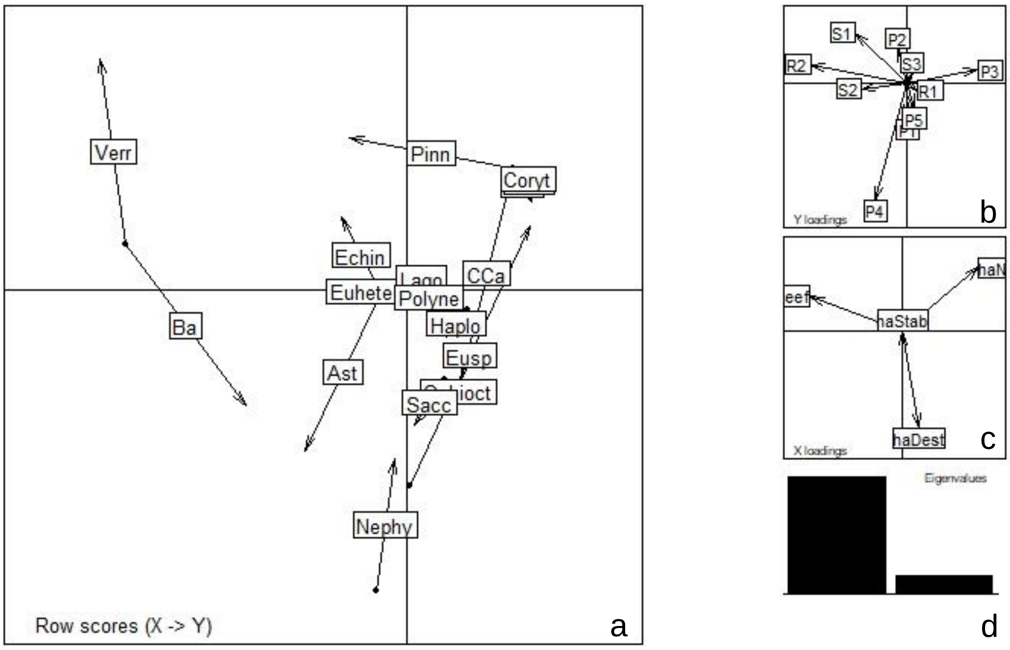

Figure E-15 CIA of habitat engineering for group B. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

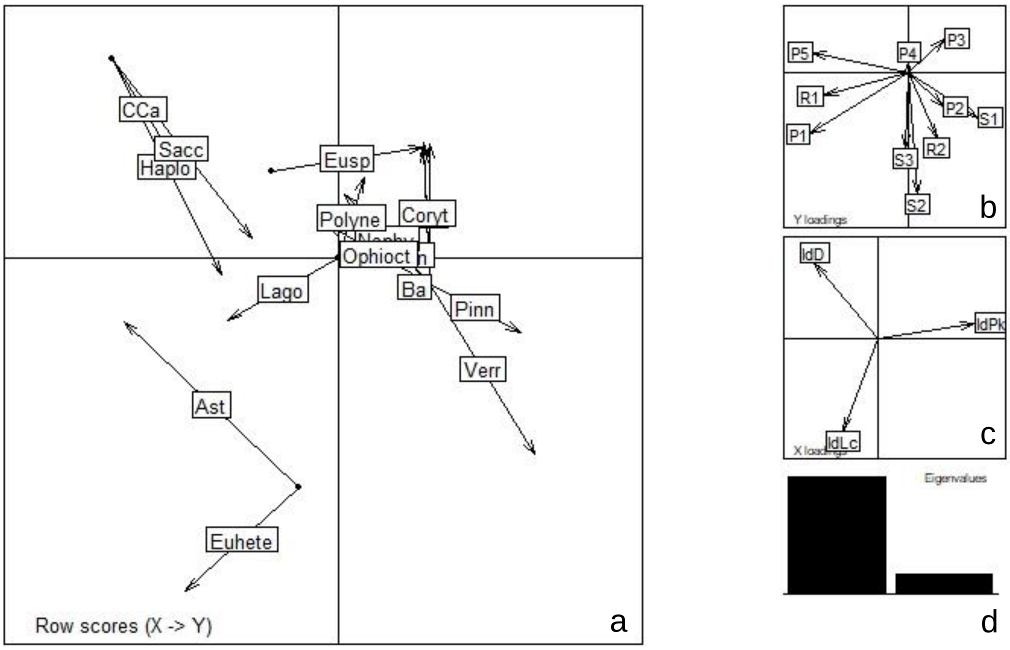

Figure E-16 CIA of larval development for group B. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

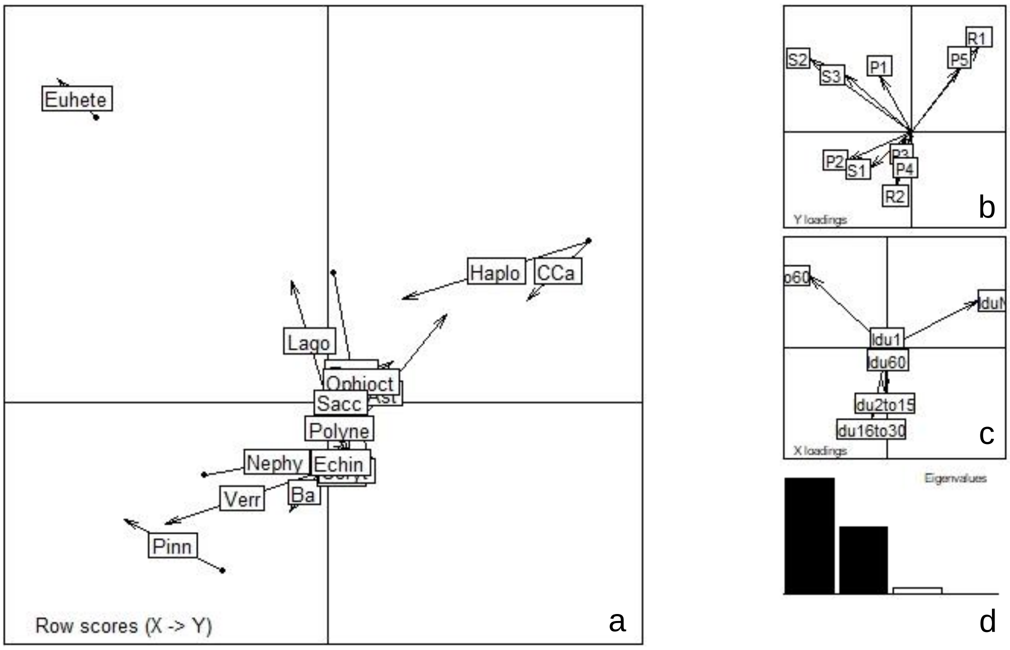

Figure E-17 CIA of larval duration for group B. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

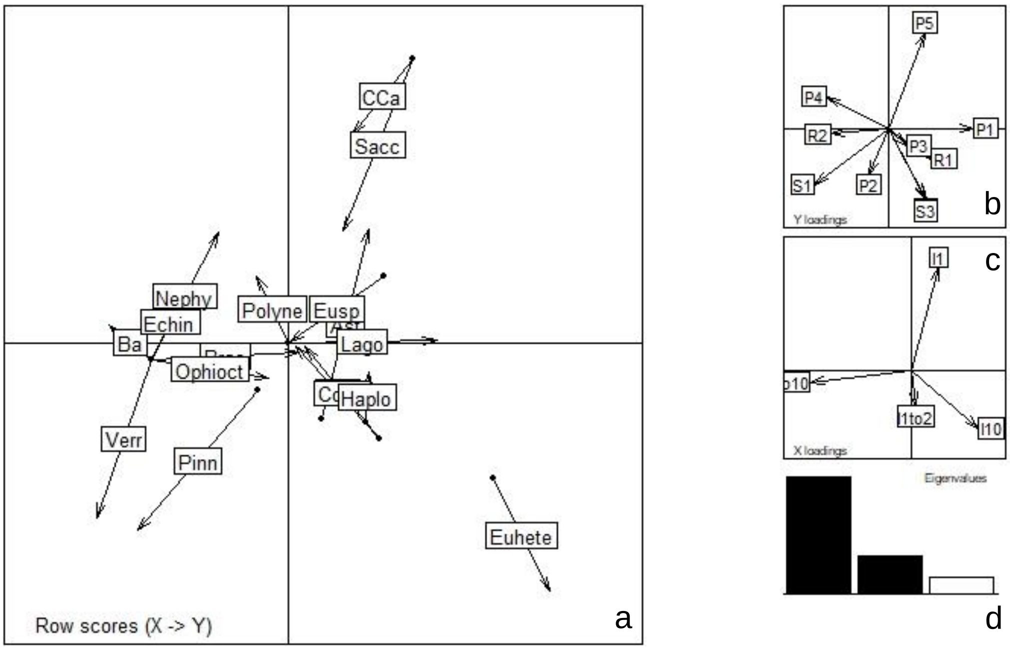

Figure E-18 CIA of longevity for group B. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

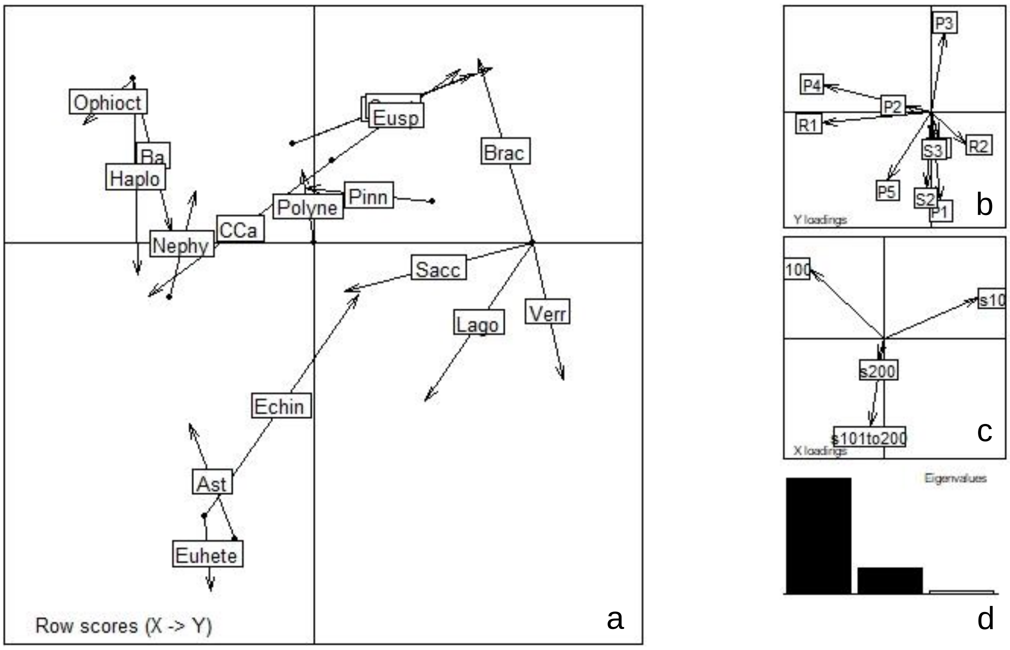

Figure E-19 CIA of maximum adult size (length or width) for group B. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

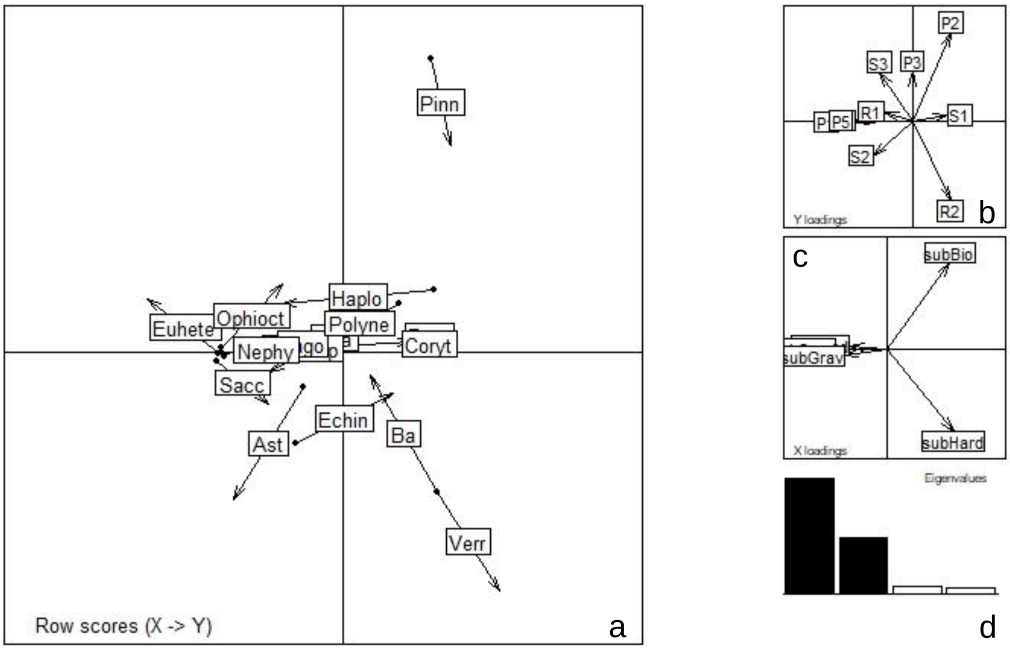

Figure E-20 CIA of preferred substrate for group B. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

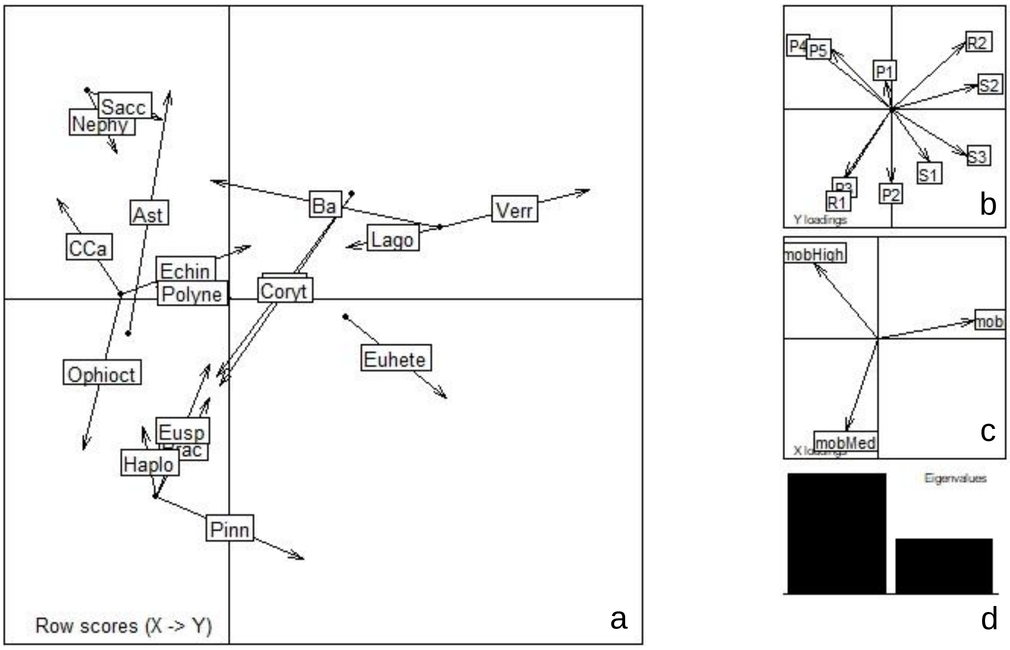

Figure E-21 CIA of strategies for displacement for group B. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

E.3 Group C

For taxa in group C, labels have been removed from graphics to aid interpretation.

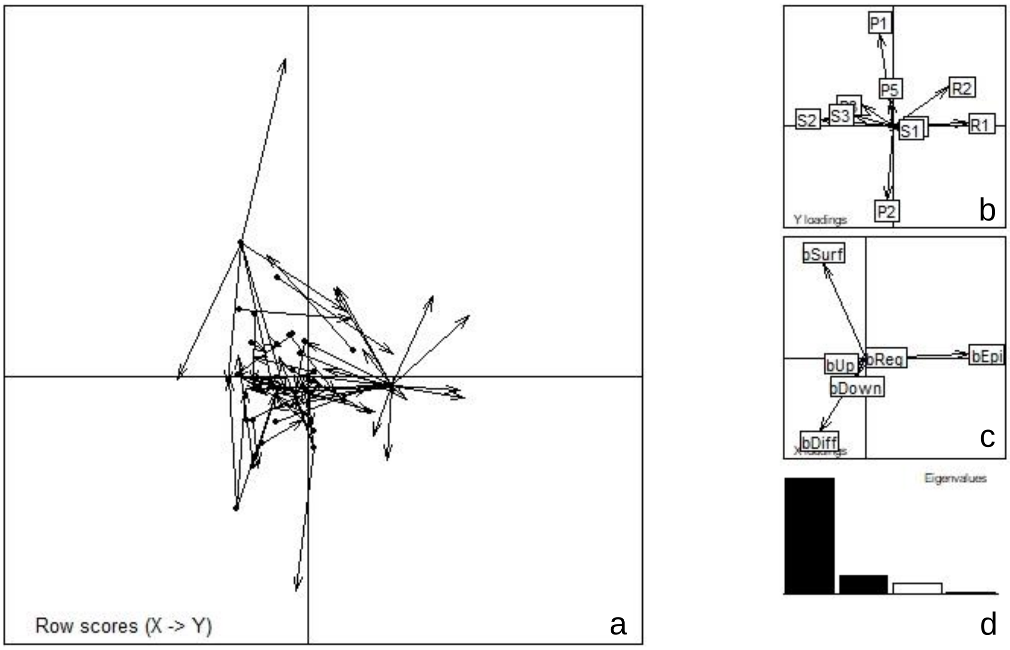

Figure E-22 CIA of bioturbation for group C. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

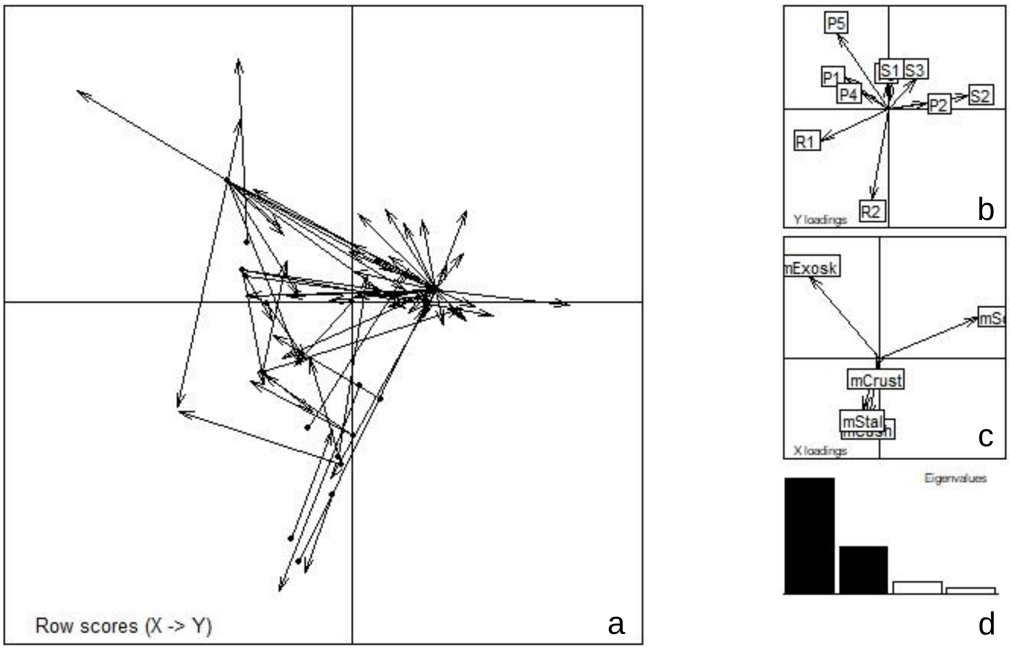

Figure E-23 CIA of body shape for group C. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

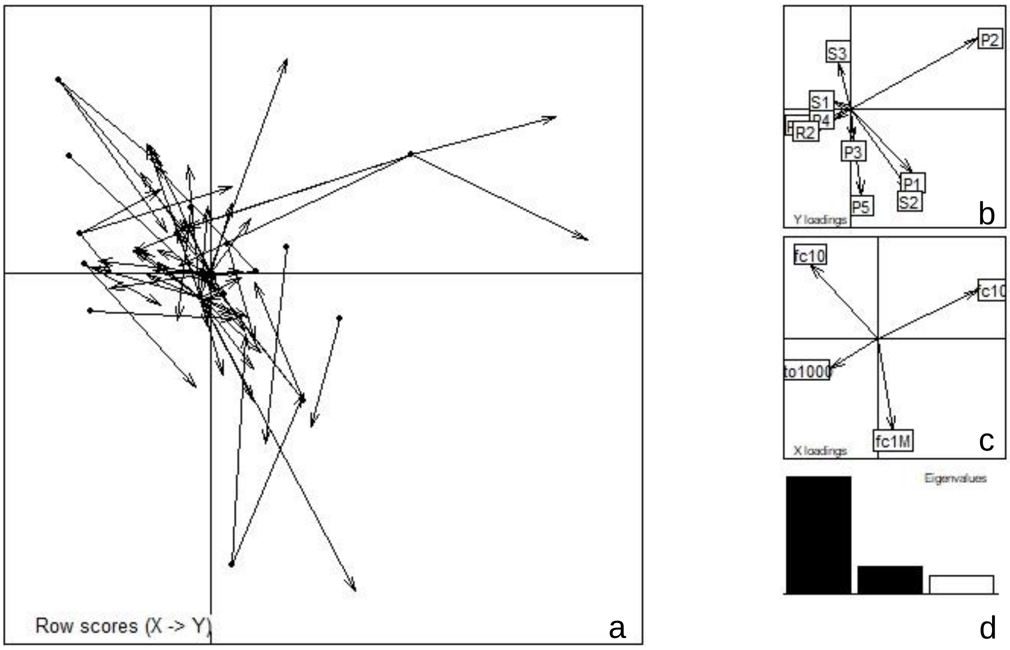

Figure E-24 CIA of fecundity for group C. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

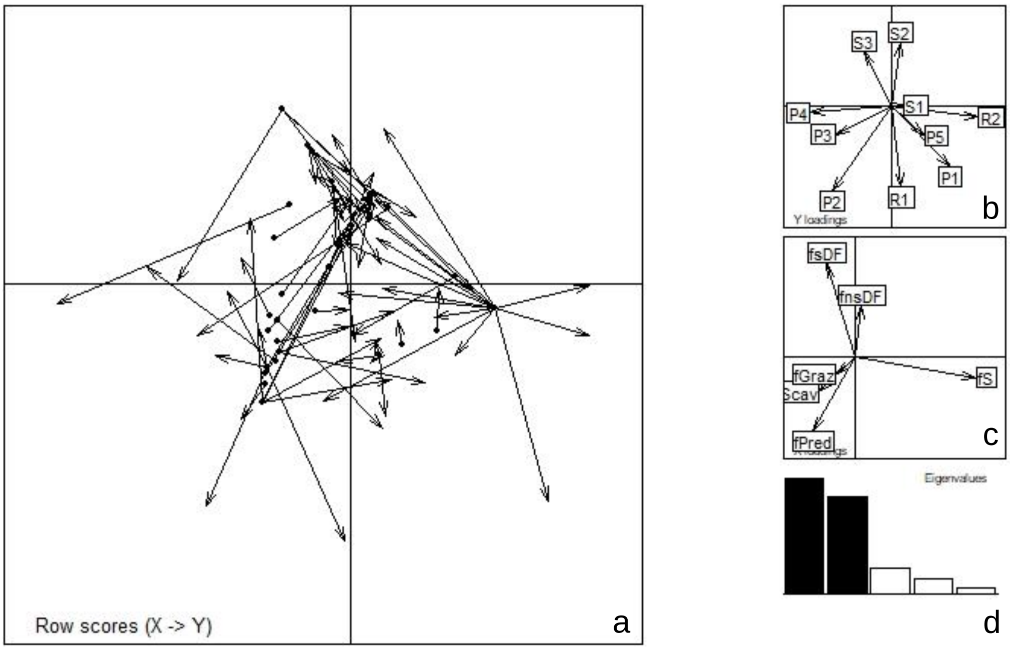

Figure E-25 CIA of feeding mode for group C. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

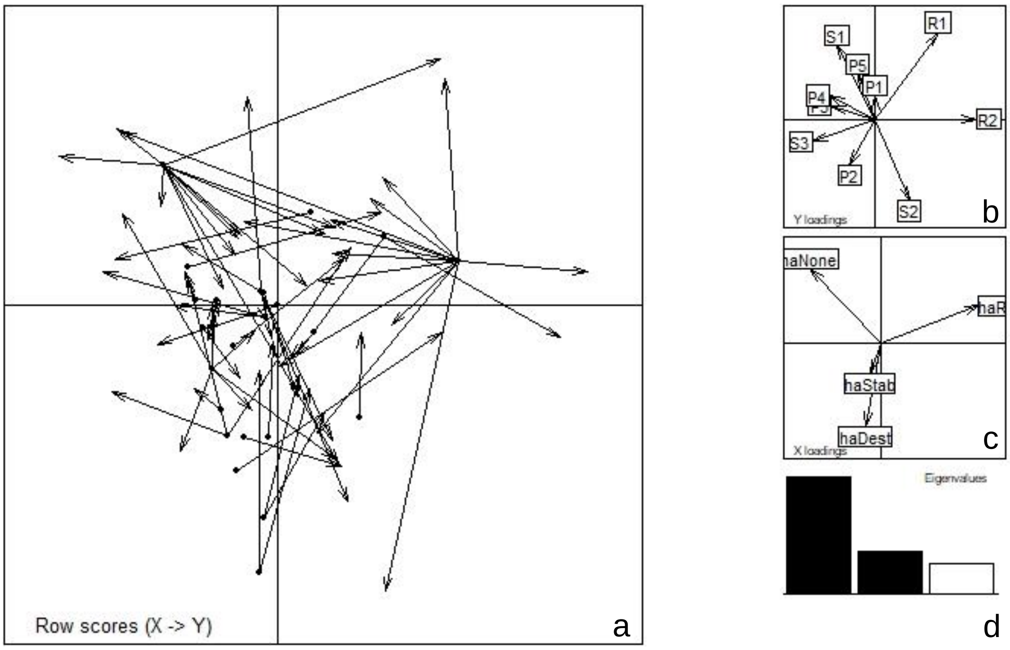

Figure E-26 CIA of habitat engineering for group C. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

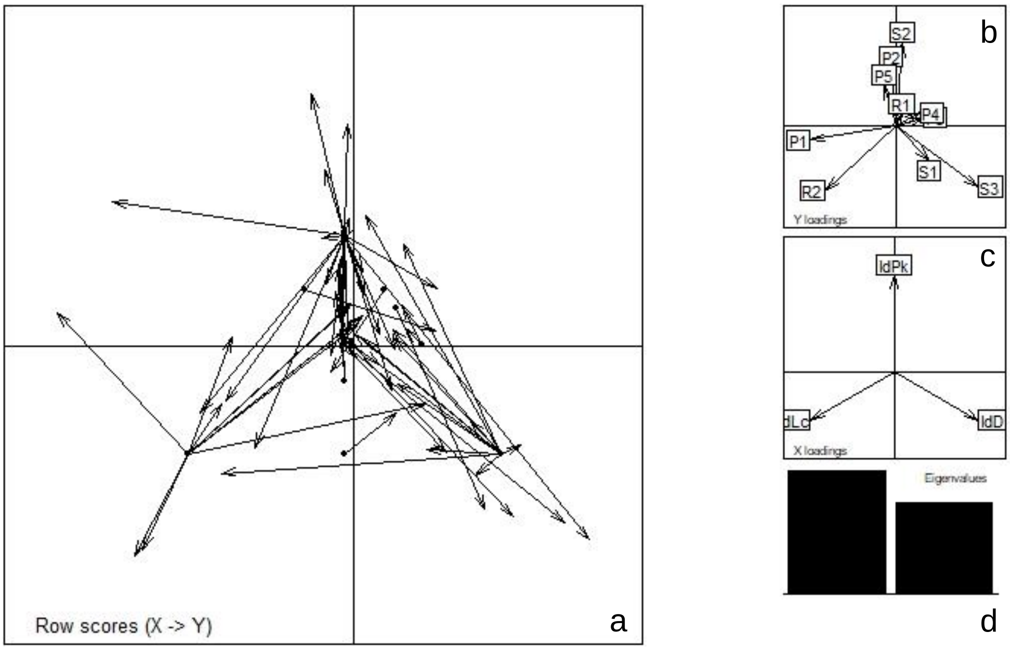

Figure E-27 CIA of larval development for group C. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

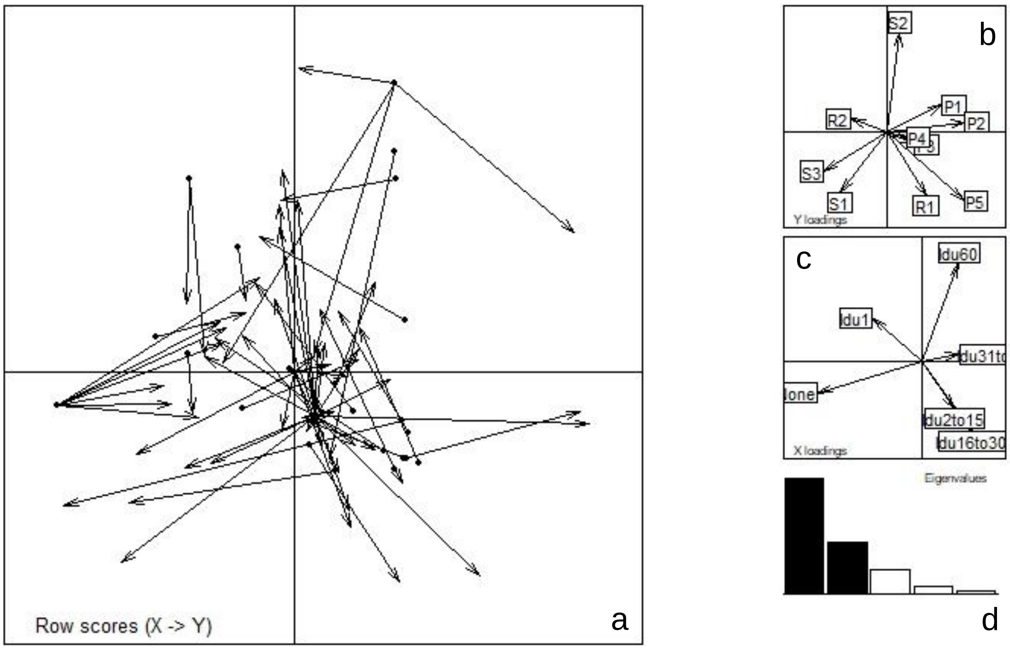

Figure E-28 CIA of larval duration for group C. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

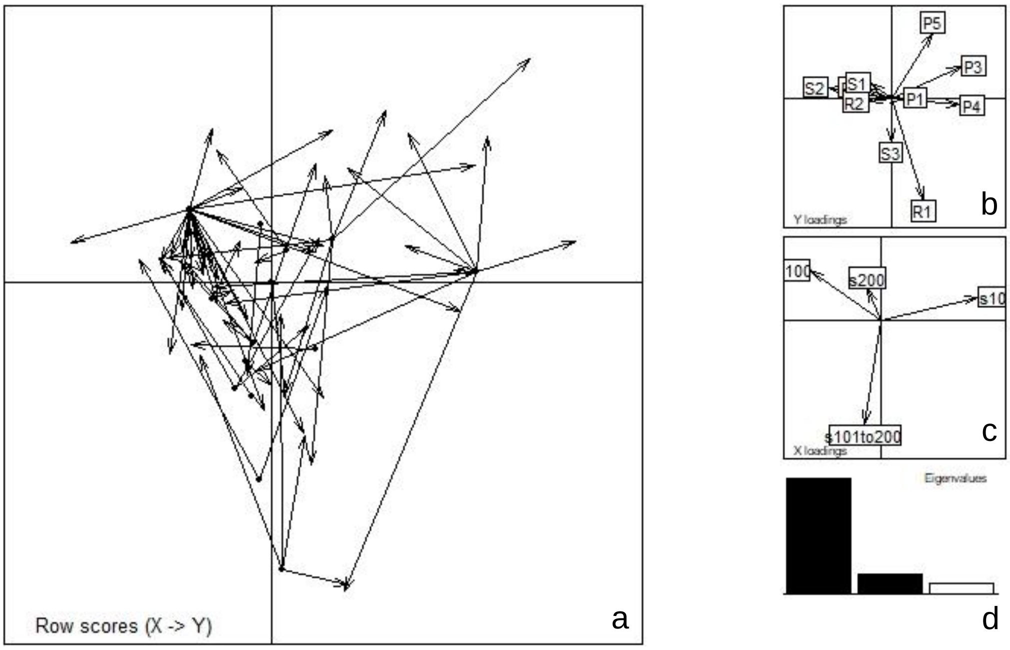

Figure E-29 CIA of maximum adult size (length or width) for group C. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

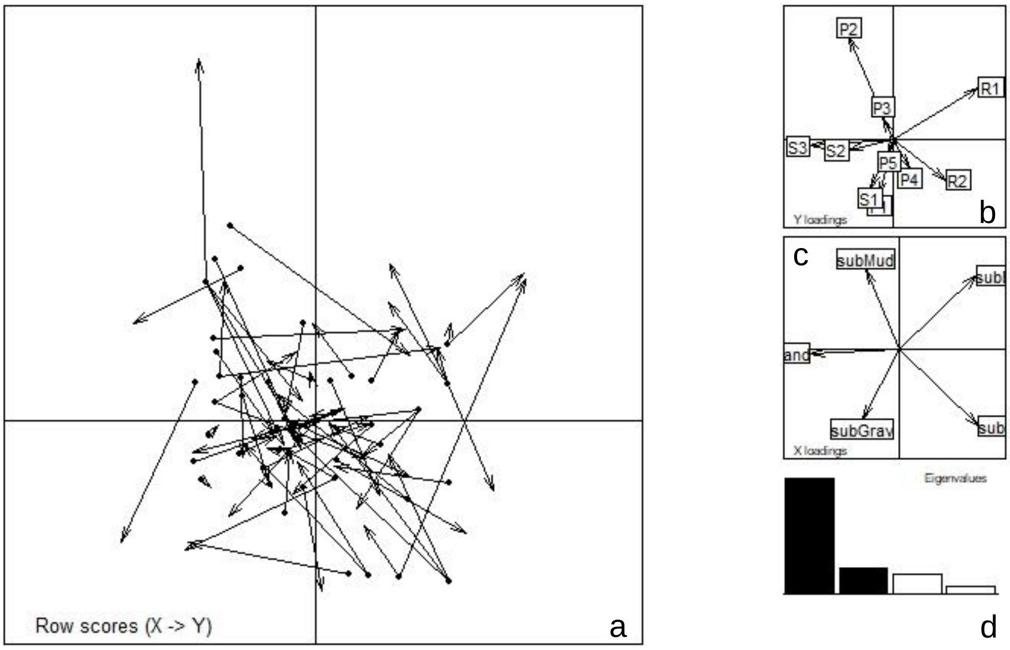

Figure E-30 CIA of preferred substrate for group C. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

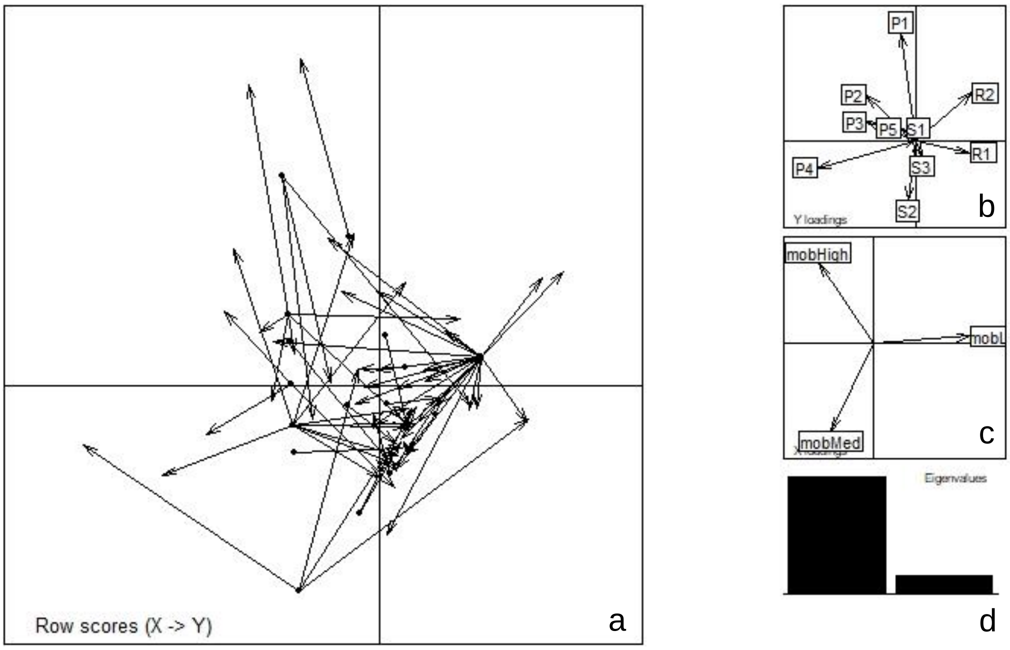

Figure E-31 CIA of strategies for displacement for group C. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

E.4 Group D

For taxa in group D, labels have been removed from graphics to aid interpretation.

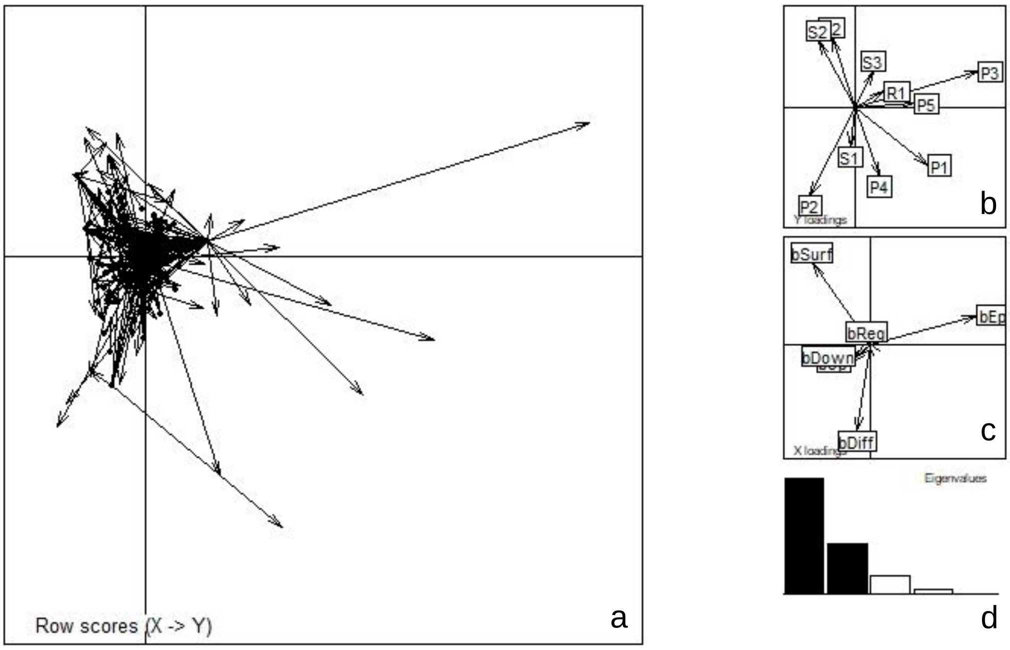

Figure E-32 CIA of bioturbation for group D. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

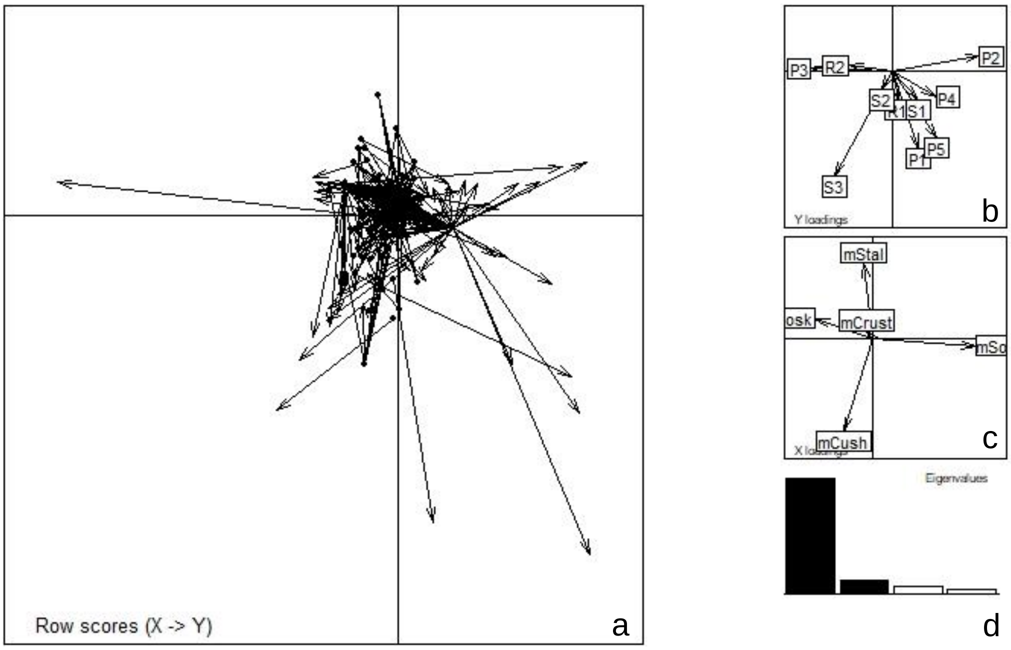

Figure E-33 CIA of body shape for group D. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

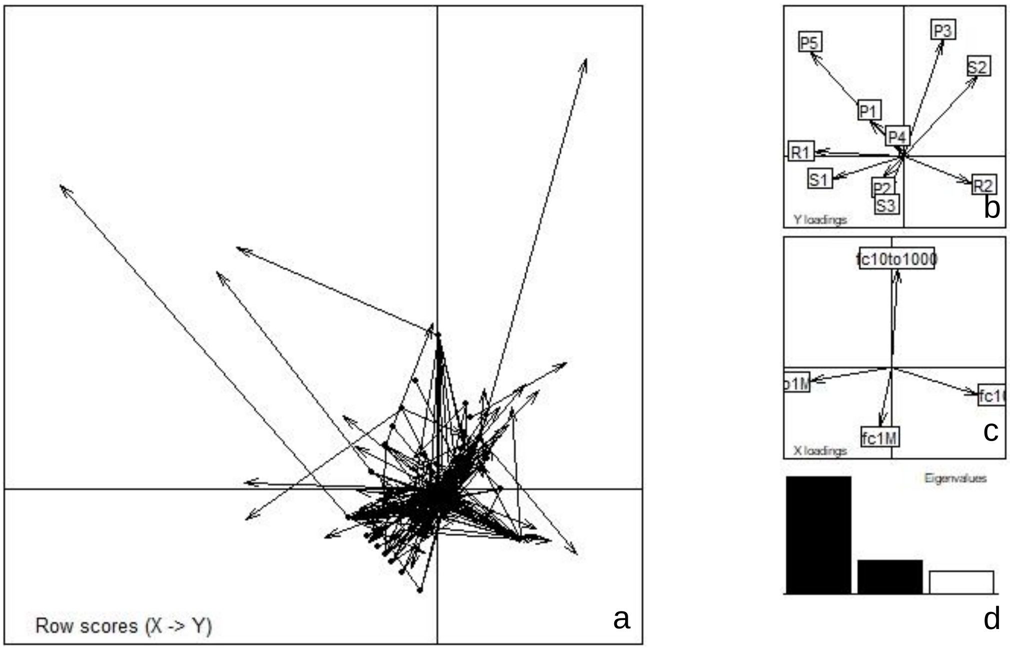

Figure E-34 CIA of fecundity for group D. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

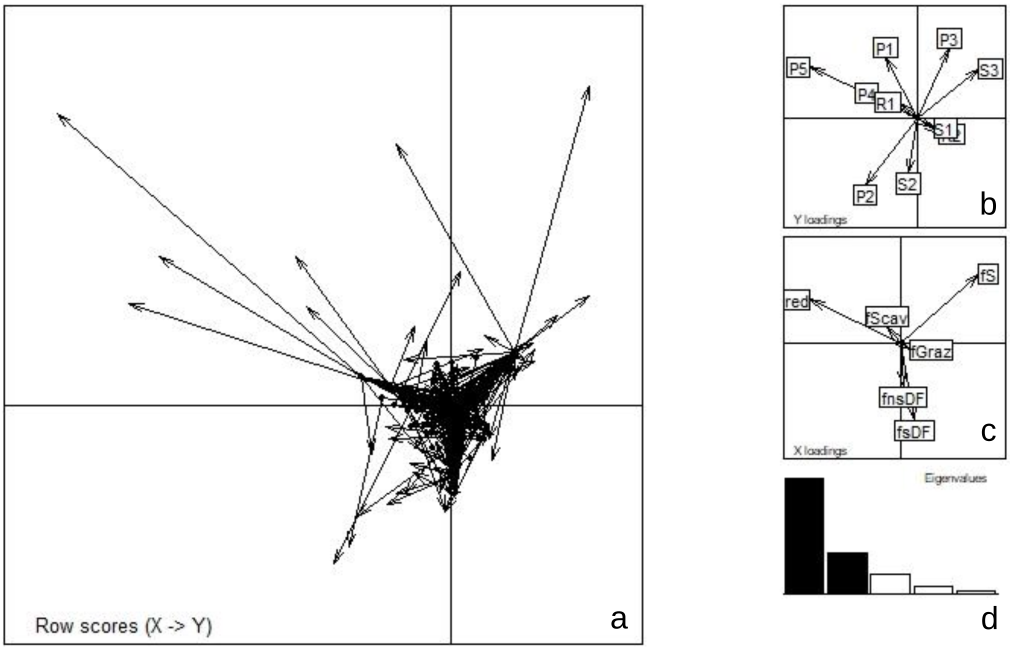

Figure E-35 CIA of feeding mode for group D. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

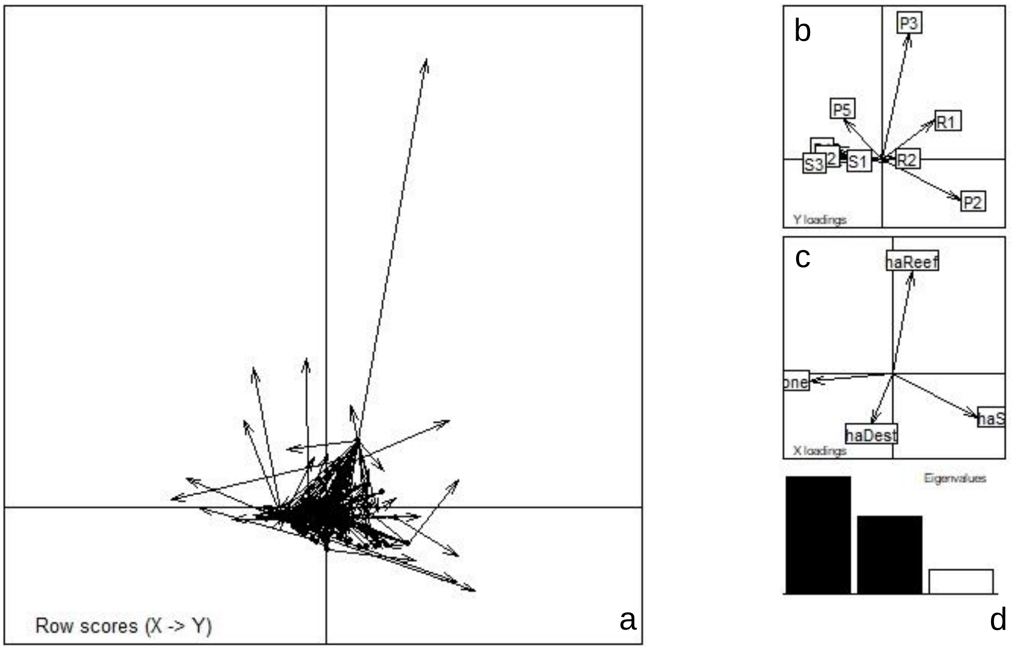

Figure E-36 CIA of habitat engineering for group D. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

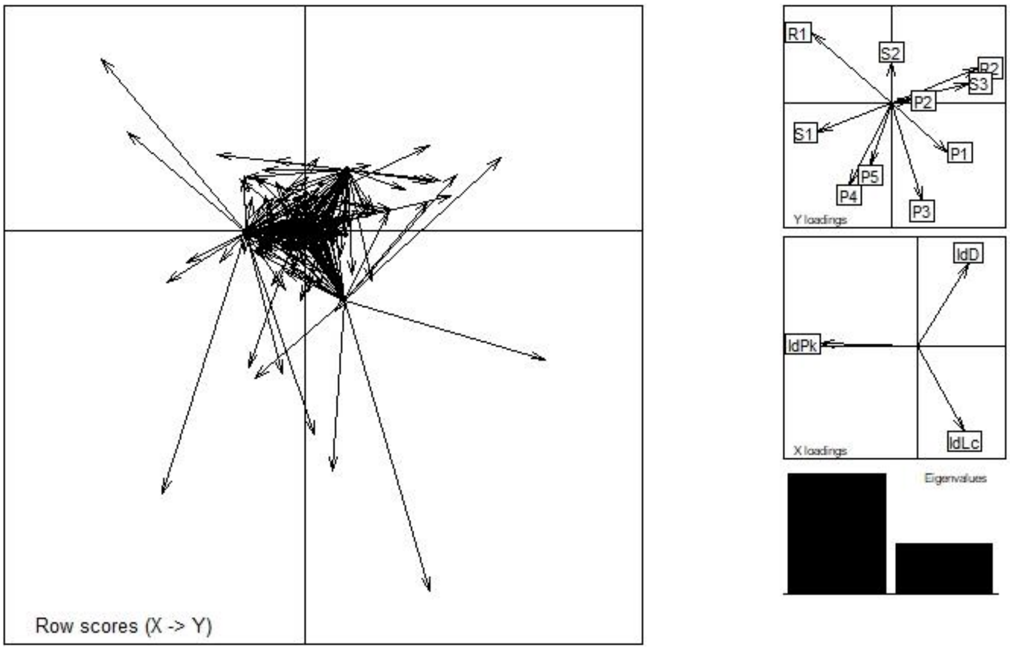

Figure E-37 CIA of larval development for group D. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

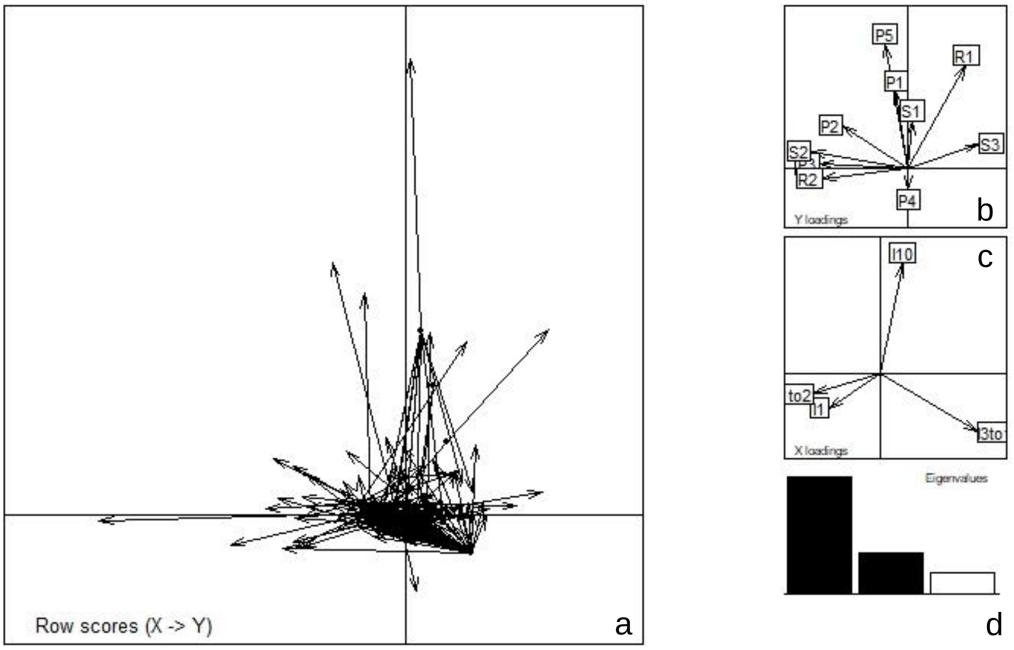

Figure E-38 CIA of longevity for group D. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

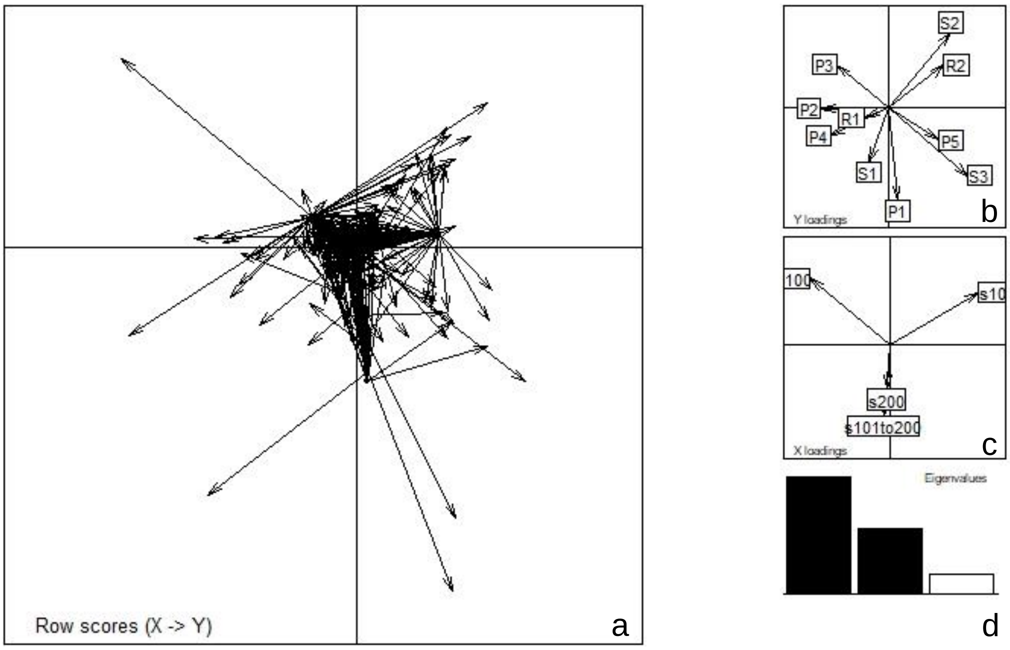

Figure E-39 CIA of maximum adult size (length or width) for group D. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

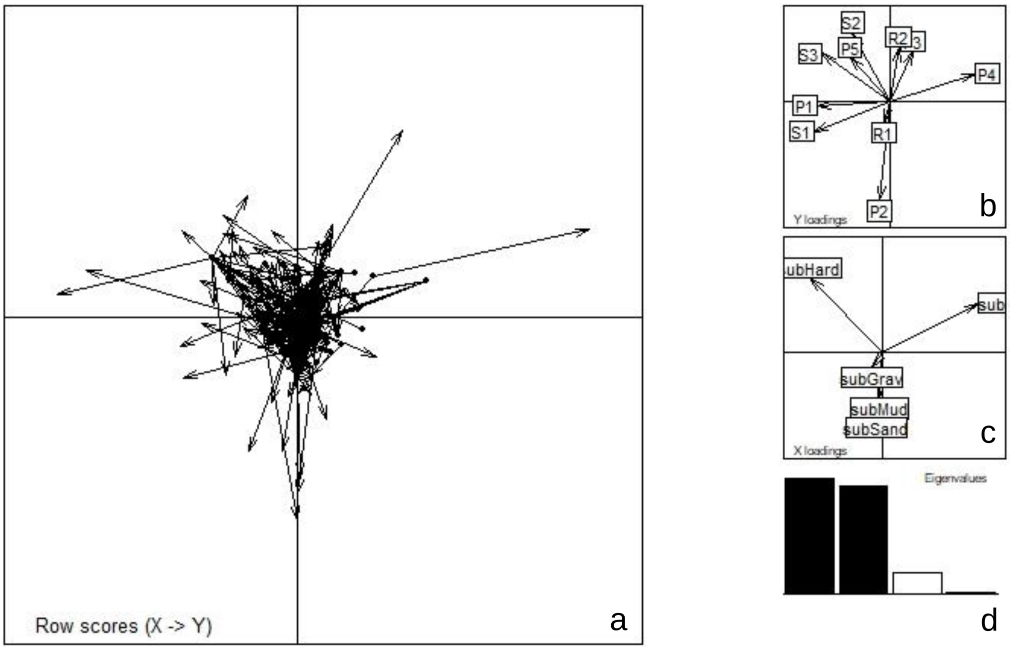

Figure E-40 CIA of preferred substrate for group D. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

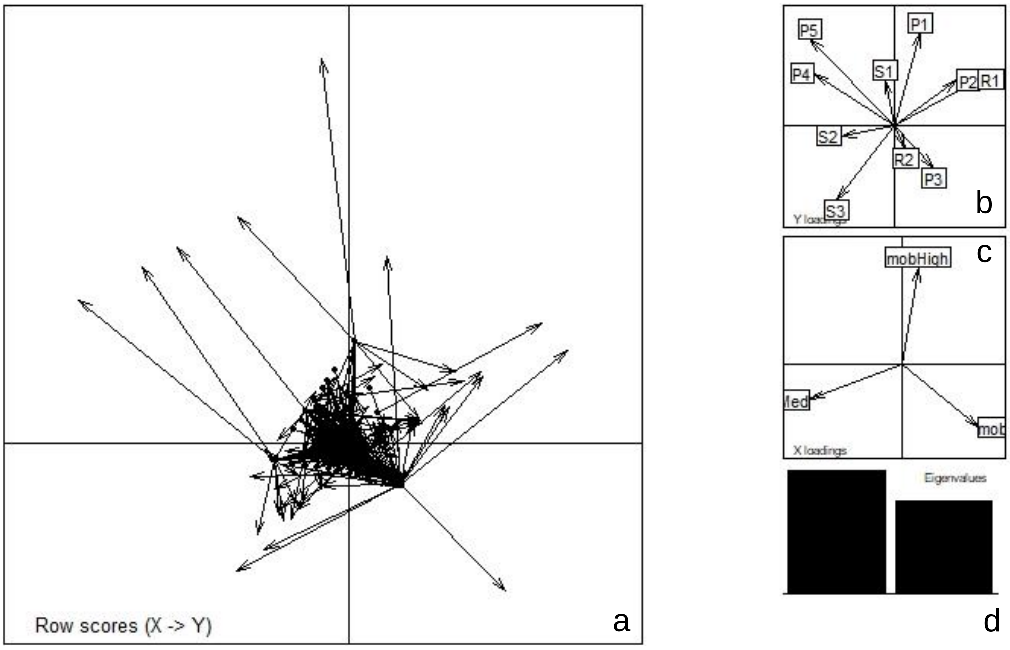

Figure E-41 CIA of strategies for displacement for group D. Arrows in the scatter plot (a) indicate correlation between sites and trait expression. Y loadings (b) represent the coefficients of sites. X loadings (c) represent the coefficients of biological traits. The screeplot (d) shows the eigenvalues for the co-inertia analysis.

Appendix F Key figures from the co-inertia analyses and Monte Carlo tests (Chapter 4.3.2.2)

Table F-1 Projected inertia (%) and correlation coefficient (RV) from co-inertia analyses for group A with corresponding simulated p-value (P) produced through Monte-Carlo tests.

Group A	Projected inertia						
Trait	**Axes 1**	**Axes 2**	**Axes 3**	**Axes 4**	**Axes 5**	**RV**	**P**
Bioturbation	76.59	16.78	5.40	1.07	0.00	0.29	0.39
Body shape	61.92	26.40	11.68	0.00	0.00	0.20	0.63
Fecundity	67.55	24.84	7.61	0.00	0.00	0.18	0.86
Feeding mode	78.08	12.21	7.70	1.88	0.13	0.19	0.90
Habitat engineering	86.62	9.56	3.83	0.00	0.00	0.22	0.59
Larval development	63.29	36.71	0.00	0.00	0.00	0.27	0.32
Larval duration	67.08	25.76	7.15	0.00	0.00	0.20	0.66
Longevity	95.75	4.25	0.00	0.00	0.00	0.30	0.12
Maximum adult size	68.69	30.96	0.36	0.00	0.00	0.16	0.79
Preferred substrate	64.04	24.07	10.51	1.39	0.00	0.28	0.49
Strategies for displacement	93.68	6.33	0.00	0.00	0.00	0.10	0.97

Table F-2 Projected inertia (%) and correlation coefficient (RV) from co-inertia analyses for group B with corresponding simulated p-value (P) produced through Monte-Carlo tests.

	Projected inertia						
Trait	**Axes 1**	**Axes 2**	**Axes 3**	**Axes 4**	**Axes 5**	**RV**	**P**
Bioturbation	67.06	32.94	0.00	0.00	0.00	0.19	0.56
Body shape	71.39	26.58	2.03	0.00	0.00	0.24	0.26
Fecundity	65.70	27.37	6.93	0.00	0.00	0.32	0.16
Feeding mode	56.32	20.81	18.04	3.56	1.27	0.40	0.03
Habitat engineering	86.67	13.33	0.00	0.00	0.00	0.30	0.10
Larval development	86.00	14.00	0.00	0.00	0.00	0.22	0.17
Larval duration	61.42	35.59	2.82	0.17	0.00	0.26	0.19
Longevity	68.00	22.22	9.77	0.00	0.00	0.24	0.49
Maximum adult size	79.98	18.08	1.94	0.00	0.00	0.22	0.25
Preferred substrate	62.21	30.17	4.32	3.30	0.00	0.18	0.64
Strategies for displacement	68.87	31.13	0.00	0.00	0.00	0.18	0.66

Table F-3 Projected inertia (%) and correlation coefficient (RV) from co-inertia analyses for group C with corresponding simulated p-value (P) produced through Monte-Carlo tests.

	Projected inertia (%)						
Trait	**Axes 1**	**Axes 2**	**Axes 3**	**Axes 4**	**Axes 5**	**RV**	**P**
Bioturbation	78.69	12.41	7.53	1.37	0.00	0.08	0.16
Body shape	63.90	26.21	6.88	3.01	0.00	0.06	0.36
Fecundity	71.93	17.11	10.96	0.00	0.00	0.07	0.54
Feeding mode	44.71	37.50	9.81	5.76	2.22	0.09	0.18
Habitat engineering	61.88	22.26	15.85	0.00	0.00	0.09	0.17
Larval development	57.57	42.43	0.00	0.00	0.00	0.05	0.59
Larval duration	57.48	25.84	11.72	3.52	1.45	0.07	0.68
Longevity	56.11	32.08	11.81	0.00	0.00	0.11	0.03
Maximum adult size	79.00	13.58	7.42	0.00	0.00	0.09	0.17
Preferred substrate	68.77	15.38	11.78	4.08	0.00	0.09	0.12
Strategies for displacement	86.88	13.12	0.00	0.00	0.00	0.06	0.44

Table F-4 Projected inertia (%) and correlation coefficient (RV) from co-inertia analyses for group D with corresponding simulated p-value (P) produced through Monte-Carlo tests.

	Projected inertia						
Trait	**Axes 1**	**Axes 2**	**Axes 3**	**Axes 4**	**Axes 5**	**RV**	**P**
Bioturbation	66.17	26.43	5.30	2.04	0.06	0.01	0.82
Body shape	59.38	28.53	7.23	4.87	0.00	0.01	0.62
Fecundity	71.81	22.43	5.76	0.00	0.00	0.01	0.71
Feeding mode	52.89	35.05	8.66	2.42	0.98	0.02	0.65
Habitat engineering	62.76	25.51	11.73	0.00	0.00	0.02	0.69
Larval development	79.02	20.98	0.00	0.00	0.00	0.01	0.66
Larval duration	78.42	16.19	3.08	1.91	0.41	0.03	0.04
Longevity	77.89	17.41	4.70	0.00	0.00	0.02	0.44
Maximum adult size	63.09	26.77	10.14	0.00	0.00	0.01	0.93
Preferred substrate	51.94	39.55	8.16	0.35	0.00	0.02	0.34
Strategies for displacement	63.11	36.89	0.00	0.00	0.00	0.02	0.21

Appendix G Photogrammetry results (Chapter 5.6.3)

Table G-1 Coastal defence groyne (Lowestoft) deviation from object surface height and thickness

	Replicate	Deviation from object surface, height above seabed (mm)				*Mean thickness (mm)*	Deviation from mean thickness, height above seabed (mm)			
		200	**500**	**800**	**1100**		**200**	**500**	**800**	**1100**
	1	6.85	7.87	9.30	10.58	*8.65*	-1.80	-0.78	0.65	1.93
Side 1	2	6.00	10.49	10.77	9.45	*9.18*	-2.65	1.84	2.12	0.80
	3	7.63	2.07	11.82	11.87	*8.35*	-1.02	-6.58	3.17	3.22
	1	5.19	2.98	0.90	8.21	*4.32*	-3.46	-5.67	-7.75	-0.44
Side 2	2	7.72	3.70	4.26	5.44	*5.28*	-0.93	-4.95	-4.39	-3.21
	3	7.92	5.52	4.95	6.04	*6.11*	-0.73	-3.13	-3.70	-2.61
	1	10.51	5.31	4.88	10.43	*7.78*	1.86	-3.34	-3.77	1.78
Side 3	2	7.49	7.65	5.51	6.43	*6.77*	-1.16	-1.00	-3.14	-2.22
	3	4.73	5.50	6.47	1.68	*4.60*	-3.92	-3.15	-2.18	-6.97
	1	4.03	9.11	11.22	3.70	*7.02*	-4.62	0.46	2.57	-4.95
Side 4	2	-0.77	4.38	2.96	2.24	*2.20*	-9.42	-4.27	-5.69	-6.41
	3	3.45	11.24	10.84	1.00	*6.63*	-5.20	2.59	2.19	-7.65

Table G-2 Pier pile (Southwold) deviation from object surface height and thickness

	Replicate	**Deviation from object surface, height above seabed (mm)**					***Mean thickness, mm***	**Deviation from mean thickness, height above seabed (mm)**				
		200	**500**	**800**	**1100**	**1500**		**200**	**500**	**800**	**1100**	**1500**
Side 1	1	-0.55	12.05	9.83	1.27	-1.81	*4.16*	-4.71	7.89	5.67	-2.89	-5.97
	2	-2.89	1.49	5.68	6.03	-1.26	*1.81*	-7.05	-2.67	1.52	1.88	-5.42
	3	-1.37	10.63	7.71	3.16	1.02	*4.23*	-5.52	6.47	3.55	-1.00	-3.14
Side 2	1	-3.17	3.12	11.34	2.33	0.14	*2.75*	-7.32	-1.04	7.18	-1.83	-4.02
	2	0.54	2.59	7.29	6.91	-0.24	*3.42*	-3.62	-1.56	3.14	2.75	-4.40
	3	1.06	3.81	7.74	6.46	0.96	*4.00*	-3.09	-0.35	3.58	2.30	-3.20
Side 3	1	-2.08	-2.12	7.79	-4.36	-9.04	*-1.96*	-6.24	-6.28	3.63	-8.51	-13.20
	2	-0.20	2.13	6.08	4.05	3.44	*3.10*	-4.36	-2.03	1.92	-0.11	-0.71
	3	0.43	2.81	6.83	2.49	2.13	*2.94*	-3.73	-1.34	2.67	-1.67	-2.03

Annexes

Published articles that were not part of the main research and were thus not included in the body of the thesis. The formatting of the articles is based on that of the original publications.

Annex A

The following article was published in Progress in the Analysis and Design of Marine Structure – Proceedings of the 6th International Conference on Marine Structures (MARSTRUCT 2017), 889-898 May 8-10, 2017, Lisbon, Portugal. http://dx.doi.org/10.1201/9781315157368-100

The Effect of Marine Growth dynamics in Offshore Wind Turbine Support Structures

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ABSTRACT: Offshore wind turbine (OWT) support structures are invariably subject to colonisation by ma-rine organisms, which are not spatially or temporally linear. Marine Growth (MG) varies based on location and season, and with structural and material characteristics. MG is a major consideration for engineers. As organisms settle on the structures, they may increase surface roughness and cross-sectional area, altering drag and inertia coefficients and increasing hydrodynamic loading. Furthermore, the added mass from MG also influences structural integrity. As such, there is considerable uncertainty surrounding the response of OWTs to MG, as this phenomenon is often overlooked in FEA modelling. This paper uses the parametric FEA model of an OWT support structure developed in [1] to analyse how different growth rates and patterns of zonation of MG affect the structural integrity of the system. MG has a great impact in the fatigue life of the structure, as a reduction of 58.6-59.2% is presented in the baseline scenarios.

1 INTRODUCTION

Offshore wind turbine (OWT) support structures are invariably subject to colonisation by marine organisms, which are believed to have an impact on OWTs structural integrity. Marine growth (MG) refers to the colonisation of submerged structures by marine organisms with sessile life stages, referred to as epibenthic organisms, and is a major challenge for engineers. As organisms settle on the structure, they may increase surface roughness and cross-sectional area, altering drag and inertia coefficients and increasing hydrodynamic loading. It can be assumed that variability in MG would lead to fluctua-tions in corresponding loading and inertia. Furthermore, the added mass from MG also influences structural integrity (i.e. buckling and natural frequency). As such there is considerable uncertainty surrounding the long-term dynamic response of OWTs to MG, as this phenomenon is often overlooked in FEA modelling.

Parametric FEA modelling is a powerful design tool often used in offshore wind. It is so effective because key design parameters (KDPs) can be modified directly in the code, to assess their effect in the structure's integrity, saving time and computational resources.

This paper uses the parametric FEA model of an OWT support structure developed in [1] to analyze how critical the MG effect is in the structural integrity of OWT support structures. A review of how the Oil and Gas Industry has approached this issue in the past and how the Offshore Wind Industry can benefit from their knowledge is presented in Section 2. Section 3 shows a summary of the baseline tur-bine and parametric FEA model developed in [1], along with the loading conditions presented in Sec-tion 4. ULS, FLS, buckling and natural frequencies are investigated against different growth rates and patterns of zonation and presented in Section 5. Finally, results and conclusions can be found in Section 6 and 7.

2 MARINE GROWTH

Settlement of epibenthic organisms is determined and influenced by multiple factors including season, species presence, life cycle and life stage requirements, prevailing environmental conditions, and features and characteristics of the substrate.

Seasonal variation in settlement is evident from a number of studies [3, 4]. In the North Sea biomass has been shown to peak in the summer, with lowest levels observed in the winter and spring [4]. This is supported by [3], who reported that species richness increased from February to July, with densities increasing 10-20 fold in the southern North Sea. In addition, surveys of a Belgian offshore wind farm in 2008 and 2011 have demonstrated seasonal variabil-ity in epibenthic coverage. Down to a depth of -2 m Mytilus edulis coverage varied from 0-60% in February but increased to 90-100% in September [4].

Early research on colonisation stemmed from the observation that, on rocky shores, organisms occupied distinct bands both above the waterline and below. It is now well known that this pattern of zonation is a result of localized environmental characteristics forming small scale habitats resulting to varying levels environmental parameters, such as nutrient transport, current regimes or wave exposure. Indeed, exposure to wave action can influence the distribution and morphology of epibenthic organisms. Shell lengths in dogwhelks, Nucella lapillus, have been found to be shorter and wider on exposed shores whilst having elongated, narrower spires at sheltered locations [5]. Wave exposure has also been shown to effect growth rates in epibenthic invertebrates. Waves and water flow influence light levels, oxygen and sediment movement and nutrient availability [6]. Maximum growth rates have been found in areas with intermediate levels of exposure, with highly exposed and highly sheltered locations showing a sharp reduction in growth rates [7]. Indeed, impact of waves place hydrodynamic forces on epibenthic invertebrates, such as mussels, and may cause them to become damaged or dislodged [9, 13]. Therefore, settlement and post settlement survival may be reduced in areas of heavy wave ac-tion.

Similar patterns have been found on offshore structures. Zonation in relation to depth has been described in communities colonising offshore oil and gas platforms as well as wind turbine substructures [4]. Southgate and Myers [10] found that, for the Celtic Sea Kinsale Field gas platform, mussels of Mytilus spp formed the dominant colonising organism between 6 and 20 m. Whilst, between -20 m and -30 m the soft coral, Alcyonium digitatum, and anemone, Metridium senile, dominate. At depths be-low -30 m Serpulid worms are the dominant organisms. In the case of the Montrose Alpha North Sea oil platform mussels were absent and down to -10 m epibenthic communities were dominated by macro algae, with arborescent bryozoa and hydroids [11]. However below -10 m macro algae gave way to arborescent bryozoa and hydroids and below -30 m hydroids, calcareous and encrusting bryozoa domi-nated [11].

The effects of wave action on growth rates and post settlement mortality or dislodgement of epibenthic organisms has received less attention in relation to offshore structures than on rocky shores. However, it is likely that areas of structures exposed to wave action would also show variation in MG over time and between seasons, as winter storms would increase wave action. It is also likely that variation in growth would be seen between shel-tered and exposed areas of structures.

MG can increase surface complexity and roughness on marine substructures, which provides new habitat and secondary substrate for colonisation. For example, mussels have been found to provide secondary hard substrate and shelter for other epibenthic species on oil and gas platforms as well as wind turbine monopiles [8, 5].

Surface complexity, orientation and roughness are known to be important for settlement of invertebrates [9, 12]. On spatial scales of µm to cm, sub-stratum topography or quality can affect survival after settlement of barnacles, hydrozoans and bryozoans [15]. Rough surfaces may increase survival rates as pits and crevices provide refuge from predators and physical disturbance. This was noted by Walters and Whethey [15] who found that in species with limited attachment ability post settlement survival was greatly increase on plates with rough surfaces.

Although MG is an important consideration in the design and operation of offshore structures, the dynamic response of epibenthic communities has not been fully realized by engineers. Indeed, it has been stated in recommended standards that MG ‘tapers off after a few years’ [16]. Whilst there is evidence supporting the idea of succession following a predictable pattern [17] it is expected that even an ecosystem with a mature community will experi-ence cyclical change. Thick layers of growth can become dislodged, particularly by storms in the winter period, creating patches of new substrate for colonisation [4]. Furthermore, artificial structures present habitat for invasive species. In the North Sea and Baltic Sea invasive species have been rec-orded on offshore wind turbine substructures in [18]. It is possible that competition between introduced and indigenous species could result in changes to the surface profile of structures.

3 PARAMETRIC FEA MODELLING OF OWT SUPPORT STRUCTURES

This section summarises the parametric FEA model of an OWT support structure taken from [1], which is employed in this assessment.

3.1 Geometry

The reference site is located off the coast of North Wales. The reference turbine used for this analysis consists of a 3.6MW Siemens turbine, connected to an 80m tower, a transition piece (TP) and is sustained by a monopile (MP) foundation. The MP is 31m long and is embedded 18m into the soil and submerged 11m into the ocean. The TP is 24m in length and joins together the MP and the tower. Six stoppers located in the internal surface of the TP, would allow it to rest on top of the MP. The Grouted Connection (GC), located between the TP and the MP, is used for the appropriate transmission of loads and stresses. The OWT support structure was modelled using Abaqus 6.14, which is a widely used FEA software.

3.2 Materials

MP, TP, and tower are made of steel S355 with a density of 7850 kg/m3, a Young's modulus of 210 GPa, a Poisson's ratio of 0.3 and a nominal yield strength of 355 MPa. GC's material properties are characterised by a density of 2740 kg/m3, a Young's modulus of 88 GPa, a Poisson's ratio of 0.19 and friction coefficient of 0.6 [19].

An important part of the detailed parametric model is composed by the soil-structure interaction. The soil profile considered in this analysis consists of one layer of sand and 3 layers of clay. Due to space restrictions further description of the soil model and the variation of material properties across the depth can be found in [1].

Composition of soil profiles strongly depends on the geographical emplacement; the soil profile utilised in this analysis corresponds to the North of the UK. Winkler's approach was used to represent the soil profile. This method is widely used to model the soil-structure interaction by replacing the elastic soil medium by closely spaced and independent elastic springs [20,21]. Furthermore, it is the recommended by DNV-GL [22], where the stiffness of the linear springs used in the Winkler's approach, is calculated from the p-y curves [23]. This method is used for the design of horizontal loaded piles by the American Petroleum Institute (API) code [24], and it calculates the lateral soil resistance (p) as a function of lateral soil displacement (y).

3.3 Mesh

A mesh sensitivity analysis was performed in order keep a balance between the computational time of the simulations and the accuracy of the results. After the analysis, a mesh size of 0.1m for the whole system was found to be adequately accurate as results had already converged. C3D8R elements are used (eight-node brick element with reduced integration).

3.4 Validation

The validation of the parametric model was carried out comparing the results of the modal analysis of both the structure and the tower, against data from the reference OWT and can be found in [1].

4 LOADING CONDITIONS

4.1 Wind

For representation of wind climate, a distinction is made between normal and extreme wind conditions. The former generally concern cyclic structural loading conditions, which are important for fatigue assessment, while the latter are wind conditions that can lead to extreme loads, which might lead to the collapse of the structure due to excessive loading [25]. Both normal and extreme wind conditions used in this analysis were calculated in ac-cordance with IEC 61400-1 [26].

4.2 Wave

Wave loading is another environmental load that influences the structural integrity of OWT support structures. Wave forces are calculated using Morrison's Equation [27], which is characterised by the inertia and drag terms, composed by their coefficients (Cm and CD respectively). Morrison's Equa-tion can be expressed as:

$$dF_t = dF_M + dF_D = C_M \rho \pi \frac{D^2}{4} \ddot{x} dz + C_D \rho \frac{D^2}{2} |\ddot{x}| \dot{x} dz$$

where represents the undisturbed fluid velocity, the acceleration of the fluid (calculated for the baseline turbine in [1]), the water's density and D the effective diameter (including MG). According to [16], most of the variation in CD and CM due to MG is produced by variations in: relative surface roughness (e = k/D), Reynolds number ($Re = \rho \dot{x} D / v$), Keulegan-Carpenter number ($KC = \dot{x} T / D$), and the member orientation. Being the kinematic viscosity of water, the period of oscillation and k is the absolute roughness height.

Mass and drag coefficients, CM and CD, are usually estimated according to the offshore standards [22] and [16] by firstly, deriving the drag coefficient for steady-state flow (C_{DS}) and the wake amplification factor ($\psi(K_c/C_{DS})$), which depends on KC and CDS.

There is a high dependence of CDS on relative surface roughness, as shown in [16]. Natural MG on platforms will generally have $e > 10^{-3}$. The MG used in these case studies is in the range from 0.015< e >0.002. CM and CD coefficients were calculated from the tables present in [16], for each one of the different MG cases. These can be found in Table 4.

4.3 Tidal and current induced loads

Tidal currents and wind driven currents are two environmental loads in which MG can have an impact and vice versa. Even though they do not represent major hazards to the structure's integrity in shallow waters, they contribute to other major excitations such as those produced by the wind and waves. The tidal current profile can be represented as the current speed at distance z, from still water level (positive upwards), which is the exponential variation of the current at still water level through the distance to the top of the water column z.

4.4 Hydrostatic Pressure

Hydrostatic pressure is referred to the pressure of the water column applied to the submerged parts of the MP and TP. It can be calculated from a control volume analysis of an infinitesimally small cube of fluid and simplified as density and gravity are con-stant through depth as in [1].

4.5 Nacelle's and Rotor's Weight

Since the nacelle's and rotor's (composed of the hub and blades) detailed modelling is not part of the parametric model, they are included in the FEA as concentrated or distributed masses in order to be able to reproduce accurately the OWT's structural behaviour. According to [28], there is no need to model the blades due to the fact that, aside from the mass added to the tower top, parked and feathered blades have minimal impact on the natural frequency of OWTs. The nacelle's and rotor's weights are 125 and 95 tons respectively, which makes a total of 220 tons that are accounted as a cylinder three metres high and with the same diameter as the top of the tower. The density was increased accordingly in order to account for the total weight. The nacelle's and rotor's weights were found in the official Siemens SWT-107 3.6 MW brochure [29].

5 EFFECT OF MARINE GROWTH IN OFFSHORE WIND TURBINE SUPPORT STRUCTURES

5.1 Limit States Formulation

Structural integrity of the system is checked according to DNV-OS-J101 [22]. Four limit states are considered in the design: ULS, FLS, Accidental Limit State (ALS) and Serviceability Limit State (SLS). Modifications in the design are checked upon ULS and FLS. ALS was not considered as this limit state is used for the assessment of structural damage in the structure, caused by accidental loads or to re-assess the ultimate resistance and structural integrity after damage. Similarly, SLS was not taken into account as it considers tolerance criteria applicable to normal use of the OWT support structures. Furthermore, the structural performance of the system was also checked upon buckling and natural frequencies.

5.1.1 ULS:

ULS analysis is carried out considering extreme environmental conditions the worst-case scenario for a 50-year return period. This is when wind, wave, tides and wind driven currents are aligned in the principal direction of the wind. The load factor to be used when different loads are combined to form the design load is 1.35 [22].

Table 1 shows the Maximum Utilisation Rates (MUR) for the MP the baseline case, which will be used to assess the loss or gain of the structural integrity of the different design cases considered.

5.1.2 FLS

FLS refers to the cumulative damage in the structure due to cyclic loads. The fatigue design of OWT support structures is governed by dynamic responses from simultaneous aerodynamic and hydrodynamic loads [30]. The load factor in the FLS is 1.0 for all load categories [22]. Normal sea state conditions (significant wave height and peak spectral period) were used for the calculation of wave loading [31]. Wind loads were taken from [32], where the fatigue thrust load for the tower of a 3.6 MW offshore wind turbine with 100m hub height are 143 kN.

S–N curve approach is the recommended by the standards [22] and [31]. Furthermore, the equivalent stress range (ΔS) can be determined from the parametric FEA model subjected to the before mentioned fatigue loads. Having obtained the equivalent stress range, the number of loading cycles to crack initiation can then be determined from the S – N curve.

The selection of the S – N curve plays a massive role in the results obtained. Offshore structures are prone to corrosion development due to the harsh marine environment, which leads to significant levels of damage to the structures and hence a reduction in service life [33]. For that reason, curve D in seawater with adequate cathodic protection is used in service life calculations [34]. Table 1 shows the stress range ΔS and the expected service life in the baseline turbine.

5.1.3 Buckling

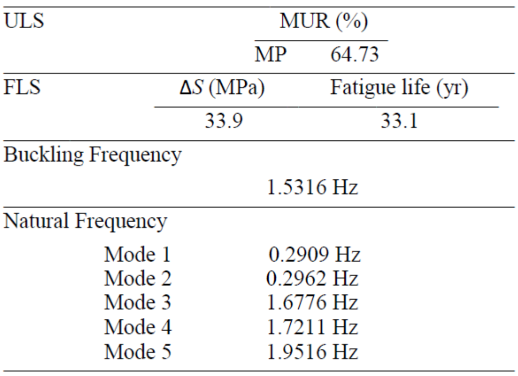
Buckling is characterised by the sudden failure of a structural member subjected to high compressive stress, when this is, at the point of failure, less than the ultimate compressive stress of the material. When the applied load is increased on a slender structure, such as a WT, there is the possibility that it becomes large enough to cause the structure to lose its stability and buckle.

Eigenvalue linear buckling analysis is generally used to estimate the critical buckling load of the analysed structure. The buckling loads are calculated relative to the base state of the structure. The buckling stability of shell structures is often checked according to DNV-RP-C202 [35] or Eurocode 3/ EN 1993-1-1 and Eurocode 3/ EN 1993-1-6. In this analysis Abaqus CAE is used to assess it. Table 1 shows the buckling frequency in the baseline turbine, being the buckling frequency for a particular load combination, the inverse of the utilization factor for the structure to buckle.

5.1.4 Natural frequencies

A classic aspect of good structural design lies in optimizing stiffness-to-mass ratio through material and shape choices. Natural frequencies' sensitivity analysis was carried out for the different case studies with the aim to detect patterns of change in the characteristic natural frequencies of the structure. Table 1 shows the first 5 eigenfrequencies of the baseline turbine.

Table 1. Structural properties of the baseline OWT



ULS	MUR (%)	
	MP	64.73
FLS	ΔS (MPa)	Fatigue life (yr)
	33.9	33.1
Buckling Frequency		
	1.5316 Hz	
Natural Frequency		
Mode 1	0.2909 Hz	
Mode 2	0.2962 Hz	
Mode 3	1.6776 Hz	
Mode 4	1.7211 Hz	
Mode 5	1.9516 Hz	

5.2 Case Study 1: Effects of Zonation

This section analyses the impact that two different MG profiles have in the structure's integrity and modal frequencies. As pointed out in previous sections, MG profiles can substantially vary depending on a number of factors. For this case study, two different profiles were developed based on existing data from the North Sea and Irish Sea [4,10]. The submerged part of the structure is 11m. Three different zones and the types of MG for each of the two profiles are presented in Figure 1. In these cases, the thickness on the exposed part of the structure were assumed to be smaller based on dislodgement through hydrodynamic pressure. However, this assumption may not always hold true in nature.

Table 2 shows the material properties for each of the zones of the two profiles. In order to introduce MG in the parametric FEA model, two half, hollow, circular cylinders are made for each zone, to surround the MP. One of these was positioned in the side of the MP exposed to currents and waves and its thickness is denoted as *Ex. Thickness* and the other half was positioned in the sheltered side and therefore is denoted as *Sh. Thickness.*

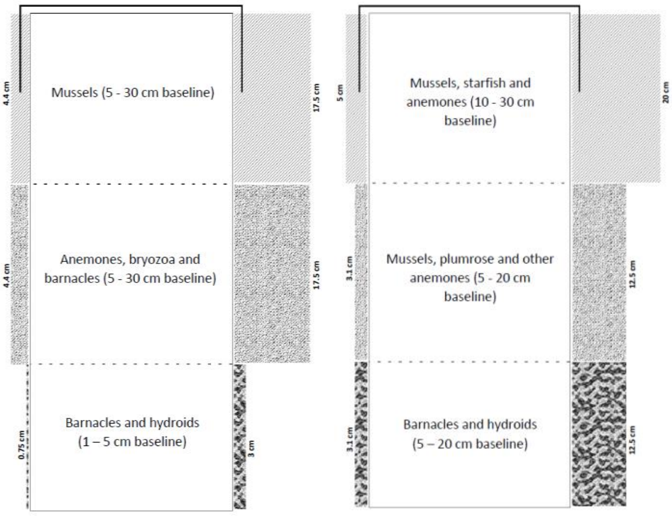


Figure 1 species zonation and variability in thickness under two case studies. Profile A (left) and Profile B (right).

Relevant material properties of the different species, like bulk density (ρ), thickness, Young's Modulus (E) and Poisson's ratio (υ), have been carefully taken from relevant literature [37, 38].

Table 2. Profile's material properties of the baseline OWT

Profile		ρ	Thickness (cm)		E	υ
& Zone		(g/cm^3)	Sh.	Ex.	(GPa)	-
A	I	3.1 [37]	17.5	4.4	0.85 [37]	0.5 [37]
	II	0.7^{*} [38]	17.5	4.4	1.27^{*} [38]	0.3 [36]
	III	0.6 † [38]	3.0	0.8	$1.13^{\dagger}$ [38]	0.3 [36]
B	I	3.1 [37]	20.0	5.0	0.85 [37]	0.5 [37]
	II	3.1 [37]	12.5	3.1	0.85 [37]	0.5 [37]
	III	$0.6^{\dagger}$ [38]	12.5	3.1	$1.13^{\dagger}$ [38]	0.3 [36]

* Values correspond to the average value plus the standard deviation.

† Values correspond to the average value minus the standard deviation

5.3 Case Study 2: Effects of Thickness

In this section a sensitivity analysis of the MG thickness, both at the exposed and the sheltered parts of the MP, of the two profiles presented in the previous section, was developed. The mean value of the range of thicknesses at different depths presented at Figure 1, was the one used in the previous Case Study. Case Study 2 analyses the effect that these ranges of thickness have in the structural integrity of the unit. Table 3 presents the different cases that compose the sensitivity analysis.

Table 3. Thickness' Sensitivity analysis

Profile		Case 2		Case 1		Baseline		Case 4		Case 5	
& Zone		Sh.	Ex.	Sh.	Ex.	Sh.	Ex.	Sh.	Ex.	Sh.	Ex.
A	I	5.0	1.3	11.3	2.8	17.5	4.4	23.8	5.9	30.0	7.5
	II	5.0	1.3	11.3	2.8	17.5	4.4	23.8	5.9	30.0	7.5
	III	1.0	0.3	2.0	0.5	3.0	0.8	4.0	1.0	5.0	1.3
B	I	10.0	2.5	15.0	3.8	20.0	5.0	25.0	6.3	30.0	7.5
	II	5.0	1.3	8.8	2.2	12.5	3.1	16.3	4.1	20.0	5.0
	III	5.0	1.3	8.8	2.2	12.5	3.1	16.3	4.1	20.0	5.0

Table 4. C_M and C_D coefficients for the different MG cases

Profile		Case 2	Case 1	Baseline	Case 4	Case 5
A	C_D	0.78	0.84	0.852	0.852	0.86
	C_M	1.92	1.92	1.92	1.92	1.92
B	C_D	0.84	0.84	0.856	0.86	0.862
	C_M	1.92	1.92	1.92	1.92	1.92

6 RESULTS & DISCUSSION

6.1 Case Study 1: Effects of Zonation

Two different MG profiles typical from the North and Irish Sea were implemented in the parametric FEA model to analyse the impact that predominant species would have in the structural integrity and natural frequencies of the unit. This impact is mainly caused by the added mass of the MG and the how these species change the roughness of the structure and therefore its dynamic coefficients (CM and CD). Average values of MG for Profile A and B were used to compare the structural integrity and modal frequencies of the unit to the case where no MG exists (Table 5).

Table 5. Effect of zonation results: structural properties.

Profile & Zone	Profile A	No Marine Growth	Profile B
ULS			
MUR (%)	68.3	68.3	68.3
FLS			
ΔS (MPa)	40.4	33.9	40.5
F. Life (yr)	13.7	33.1	13.5
Buckling Freq. (Hz)	1.532	1.532	1.532
Natural Freq. (Hz)			
Md. 1	0.2913	0.2909	0.2911
Md. 2	0.2961	0.2962	0.2959
Md. 3	1.6647	1.6776	1.6587
Md. 4	1.7051	1.7211	1.6994
Md. 5	1.9547	1.9516	1.9547

Table 5 shows no significant variation either in MUR % or buckling frequencies, for both MG profiles in comparison to no MG development. The reason why these two structural checks show no variation due to MG might be due to the fact that extreme wave loading is not affected by MG. This is because extreme waves hit the turbine's support structure in a region well above the mean water level and splash zone, where MG does not develop. Therefore, dynamic coefficients are not affected and loading conditions are maintained. Hence the lack of variation.

Although the added mass does not have an influence in buckling frequency, the fact that organisms are stuck to the support structure's surface, affects the modal frequencies and deflections of the turbine. As could be expected, the presence of these organisms in the surface of the support structure increases its rigidity, increasing natural frequencies. However, the rate of variation of the natural frequencies is not high enough for MG to be considered a threat to the structure's integrity. This is due to the low rate of change and also due to restrictions on the growth of epibenthic organisms. Whilst layers of epibenthic growth of up to 300 mm may occur, intense wave action can dislodge thick layers of MG. Furthermore, a special degree of variation is observed in Mode three and four, which could potentially be used for Structural Health Monitoring purposes.

Table 5 also shows the impact that MG has in the stress range of the unit, at mudline level. Even if this variation is low, the impact that it has in the estimated service life of the structure is great. This is due the logarithmic scale present in the S – N curves. Nevertheless, the level of damage that can be expected due to MG is never going to be constant, as it will always depend on the current level of MG development, which is highly variable. Ac-cording to Table 5, Mussel dominated profiles may present a greater threat to the structure than barna-cle dominated profiles, showing a variation in ex-pected service life from 33.1 to 13.5 years for Mus-sel-dominated profiles and from 33.1 to 13.7 years for Barnacle dominated profiles.

6.2 Case Study 2: Effects of Thickness

A sensitivity analysis of the MG thickness, both at the exposed and the sheltered parts of the MP, of the two profiles was carried out. The mean value of the range of thicknesses at different depths present-ed at Figure 1 and used in the previous Case Study constitutes the baseline scenario in this Case Study. This Case Study analyses the effect that these rang-es of thickness have in the structural integrity of the unit compared to the baseline scenario of each pro-file. Table 6 presents the results for each one of the different cases that compose the sensitivity analysis.

Similar to the previous Case Study, there is no variation in the MUR and buckling frequencies in any of the cases of both profiles. This lack of varia-tion is consistent to the results of the previous Case Study. This is because it is unlikely that the added mass from the positive variation in thickness of Cases three and four would impact the structural behaviour, when the transition from the "no MG scenario" to the baseline MG did not.

In line with the natural frequency results from the Effect of Zonation study, the rate of variation of the first natural frequency is maintained with the thickness variation and it is still not high enough for MG to be considered a threat to the structure's integrity. Besides, Modes three and four stand as the ones where higher variation in the natural frequency is seen. This fact makes them potentially useful to detect excessive MG development with Structural Health Monitoring Systems. The detection of excessive MG would be beneficial to extend the fatigue life of the structure, as according to Table 6, that constitutes the biggest threat that MG presents to OWT support structures.

Table 6. Sensitivity Analysis' results: structural properties.

Profile	Case 2	Case 1	Baseline	Case 3	Case 4
		ULS	MP's MUR (%)		
A	68.3	68.3	68.3	68.3	68.3
B	68.3	68.3	68.3	68.3	68.3
		FLS	Fatigue life (yr)		
A	14.5	14.4	13.7	13.3	12.7
B	15.9	14.0	13.5	10.2	9.7
			Buckling Frequency (Hz)		
A	1.532	1.532	1.532	1.532	1.532
B	1.532	1.532	1.532	1.532	1.532
			Natural Frequency (Hz)		
A					
Md. 1	0.2912	0.2912	0.2913	0.2913	0.2914
Md. 2	0.2960	0.2960	0.2960	0.2960	0.2960
Md. 3	1.6754	1.6701	1.6647	1.6592	1.6536
Md. 4	1.7154	1.7103	1.7051	1.6998	1.6944
Md. 5	1.9547	1.9547	1.9547	1.9548	1.9549
B					
Md. 1	0.2912	0.2911	0.2911	0.2911	0.2911
Md. 2	0.2960	0.2959	0.2959	0.2959	0.2959
Md. 3	1.6698	1.6642	1.6587	1.6529	1.6472
Md. 4	1.7101	1.7047	1.6994	1.6938	1.6884
Md. 5	1.9547	1.9547	1.9547	1.9547	1.9548

Fatigue is the structural feature most affected by MG, according to these analyses. As it can be appreciated from Table 6, MG has a great impact in the fatigue life of the structure, as a reduction of 58.6-59.2% is presented in the baseline scenarios. This impact is reduced to the 52% for the minimum MG development case, although this variation is still very high.

7 CONCLUSSION

This paper used the parametric FEA model of an OWT support structure developed in [1] to analyze the criticality of MG in the structural integrity of OWT support structures. To that aim, two MG profiles typical from the North and Irish Sea were introduced in the parametric FEA model. Due to this MG, dynamic coefficients needed to be recalculated, which also affected the loading conditions. ULS, FLS, buckling and natural frequencies have been investigated against different growth rates and patterns of zonation.

Results show no effect in the maximum utilisation ratios (MURs) and buckling frequencies, which draws the conclusion that the added mass of the MG has little or no influence in the system. Furthermore, natural frequencies were also not very affected due to this phenomenon. However, as could be expected, the presence of these organisms in the surface of the support structure slightly increases its rigidity, increasing natural frequencies in both pro-files but specially in Profile A (barnacle dominated).

Fatigue is the structural feature most affected by MG, according to these analyses. MG has a great impact in the fatigue life of the structure, as a reduction of 58.6-59.2% is presented in the baseline scenarios. This impact is reduced to the 52% for the minimum MG development case, although this variation is still very high. It is also convenient to bear in mind that MG shows considerable variability, therefore the present reduction in fatigue life is like-ly to be slightly mitigated. In conclusion, awareness should be raised to operators in order to mitigate this phenomena.

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Annex B

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Multi-Criteria Decision Analysis for Benchmarking Human-Free Lifting Solutions in the Offshore Wind Energy Environment

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Abstract: With single components weighing up to hundreds of tonnes and lifted to heights of approximately 100 m, offshore wind turbines can pose risks to personnel, assets, and the environment during installation and maintenance interventions. Guidelines and standards for health and safety in lifting operations exist; however, having people directly beneath the load is still common practice in offshore wind turbine installations. Concepts for human-free offshore lifting operations in the categories of guidance and control, connections, and assembly are studied in this work. This paper documents the process of applying Multi-Criteria Decision Analysis (MCDA), using experts' opinions for the importance of defined criteria obtained by conducting an industry survey, to benchmark the suitability of the concepts at two stages. Stage one streamlined possible options and stage two ranked the remaining suite of options after further development. The survey results showed that criteria such as 'reduction of risk', 'handling improvement' and 'reliability of operation' were most important. The most viable options, weighted by industry opinion, to remove personnel from areas of high risk are: Boom Lock and tag lines, a camera system with mechanical guidance, and automated bolt installation/fastening for seafastening. The decision analysis framework developed can be applied to similar problems to inform choices subject to multiple criteria.

Keywords: multi-criteria decision making; Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS); offshore wind turbines; health & safety; offshore lifting operations

1. Introduction

Offshore wind energy has seen considerable investment in the last decade, driven by a growing awareness of the effects of climate change and a need to diversify energy production [1,2]. By the end of 2006 the cumulative installed capacity of European offshore windfarms was approximately 1 GW, yet by the end of 2017 the total installed capacity had grown to 15.8 GW [3]. The offshore wind energy industry is set to show continued expansion and it has been estimated that the installed capacity across Europe will reach 25 GW by 2020 [3].

The installation of new turbines and continued maintenance of existing turbines will see the need for frequent onshore and offshore lifting operations. These may range from lifting large wind farm components, such as the tower or nacelle, or smaller loads such as tools, bolts, and bags.

Whilst current guidelines attempt to preclude personnel from standing or walking below suspended loads this is not always possible. Personnel are frequently beneath lifts to guide loads into position and secure them once in place, as illustrated in Figure 1a, where a team are guiding a suspended tower section into place.

Figure 1. Examples of mechanical guidance systems: (**a**) Current use of guide pins; (**b**) Guide cones for human-free met mast installation [4].

G+ (formerly G9) [5], the offshore wind health and safety organisation, is a consortium of the largest operators each contributing data on all health and safety incidents offshore which are collated into reports [6–8]. Lifting operations are particularly incident prone, consistently coming in the top three most hazardous work processes by incident number. Of these, a high proportion tends to be due to dropped objects.

Table 1 shows the total number of incidents reported each year and, of those, the number of incidents that involved dropped objects. The number of working hours and operations differed from year to year. As such total number of incidents and total number of dropped objects by the number of hours worked for each year have been calculated. This allows for scaled comparisons to be made. From the data, we can see that 2016 saw the highest number of lifting incidents and dropped objects per hour. Although the increase is relatively small it does indicate that the safety of lifts offshore has not improved.

There will always be a degree of risk in lifting operations. The probability and consequence of exposure to such risks may be reduced through careful planning, and procedures and guidelines have been put in place to ensure personnel follow safe practices. However, it is highly unlikely that failures or errors can be prevented or avoided 100% of the time.

Table 1. Total incidents and dropped objects from 2014 to 2016. [6–8] (Normalised by number of hours worked and scaled by 10,000,000.)

Area	2014	2015	2016
No. of hours worked ($\times 10^6$)	23.71	21.22	21.72
Total incidents—lifting operations	143 (6.0)	100 (4.7)	133 (6.1)
Dropped objects—lifting operations	32 (1.3)	28 (1.3)	37 (1.7)

In reviewing the detailed incident data made available by G+, it became clear that the most common incidents included dropped objects, such as tools, chains, and bolts. Equipment failure and human error were frequent causes of dropped objects. If such objects were to hit personnel, it could result in serious injury or loss of life. Thus, removing personnel from areas where falling objects could land would greatly reduce the risks to personnel.

The aim of this work is to conduct research into and assess the feasibility of methods and technologies that could reduce the need for personnel in the vicinity of lifting operations during installation of offshore wind turbines. This is achieved through employing a widely used Multi-Criteria Decision Analysis (MCDA) method combined with a review of existing technological solutions and recommendations for new ones, and a cross industry survey, which allowed the capturing of real information of the views of operators and practitioners with respect to the criteria importance when it comes to the benchmarking of concepts.

An MCDA is applied in two stages: the first stage aims to show which alternatives are the most promising and the final stage is to rank the most promising technologies. The target is to not only solve this particular problem but to also demonstrate this methodology which other researchers might apply to their own problems.

The paper is organized as follows: Section 2 presents the concepts being considered and their respective categories. Section 3 gives an introduction to MCDA and discusses the methodology employed, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method, and the industry survey used to solicit weight values. Section 4 discusses the industry survey and its results, and then follows on with the application of the MCDA. Section 5 presents the results of the MCDA and a discussion. Finally, the conclusions are presented in Section 6.

2. Wind Turbine Lifting Concepts

2.1. Guidance and Control

In this section a selection of the concepts considered in each of the three categories are presented and, where appropriate, information on the detailed work undertaken is included.

In order to lift single wind turbine components into the correct position, certain guiding and control devices, such as tag lines or guide pins, are already used. However, people are still involved in this lifting procedure; either holding the tag lines and therefore standing in the area where the part is being lifted, or directly within the installed wind turbine part in order to give commands to the crane operator. This is because the operator may not be able to see the connection at certain heights, or to manually push and guide the lifted part into its final correct position.

Mechanical tools can be classified according to their guiding orientation into two groups: guide pins or similar tools for rotational alignment of the bolt holes, and funnels or cones for centralisation. A limited number of bolts can be replaced by 'guide pins', which are slightly longer than the bolts and have a conical end. An example of such a guide pin is presented in Figure 1a. Funnels and cones allow for the centring of two elements. An example of this in practice is that of Figure 1b, where plastic guide cones were used around the flange connection of a met mast to aid the lift [4].

Visual guidance via a suitably placed banksman giving clear orders to the crane operator is simple, effective and, assuming a good protocol is established, safe. For the majority of industries and payloads, successful lifts can be achieved with the banksman positioned close enough to the lifted object without being below the load. When installing offshore wind turbine components this is rarely possible due to the marine environment and nature of the structure, hence the need for banksmen to be in potentially dangerous positions.

Ideas for moving the banksman away from the load whilst keeping the visibility of a local field are mainly based around the use of cameras. This could range from simple cameras attached to the payload, to the use of drones and 360-degree cameras with Virtual Reality (VR).

Sensorial guidance could assist in this area and potentially quantify required movement. Lasers and proximity sensors, used in a variety of applications, could be used to aid depth perception, and are used in industry for dynamic positioning of vessels, pitch and yaw measurements, and distance measurement to locate defects in bearings, shafts etc.

Automated guidance could fully automate the process. Template matching is used in several areas, such as medicine or robotics, in order to detect motions or recognise patterns or images, or also motion tracking is applied [9]. Kaur et al. [10] also studied the positioning of a load and a vehicle by means of image processing and template matching. Smart cameras are already used in robotic guidance for position detection and rotation of elements. Rahman [11] and Rinner and Guggi [12] have used smart cameras to map workshops and control cranes.

Controlling the fine motion of payloads has historically been done using tag lines, which run to the ground and can be controlled by workers below. This becomes difficult during offshore operations where, if controlled by people who are not directly beneath the load, the tag lines are limited to the location of the vessel or jack-up platform. Numerous systems are used in practice to control the fine motion and reduce sway, including the 'Boom Lock' [13] and 'Tagline Master' [14]. Additionally, installing components using a floating ship can be made easier through the use of dynamic response simulation [15].

2.2. Connections

Bolted flange connections are used in a wide range of construction industries and are a very important part of offshore wind structures. The major components of an offshore wind turbine generator (WTG), i.e., the tower sections, nacelle, and blades, are connected through bolted, ring-flange connections. Seafastening is intrinsically linked to the connection of the components because often the component is fastened to the ship in the same way in which it is fastened in construction. Flanges are welded to the grillage on the ship deck and the component, for example usually the tower section or nacelle, is bolted to the flange. However, bolting and seafastening can lead to a number of potential health and safety issues such as: unsecured loads while bolts are being applied, falling bolts during lifts, and bolts shaking loose in seafastening.

Novel connection types, reducing or eliminating the need for bolts, can be considered. These include friction connections, in which the bolts point radially outwards, are pre-installed and lowered into vertical slots [16]; temporary sliding connections which hold the section pre-bolting; and threaded connections on a large scale.

Hydraulic seafastening could be used to replace bolted connections or provide temporary stability prior to bolting. Various hydraulic systems were considered along with internal jack sea fastening; these employ pistons acting on the inner surface of the transition piece.

One obvious way to remove humans from the line of fire is to automate the tasks performed by humans. This is extremely common in factory manufacturing in a wide variety of industries where the speed, precision, and repeatability of robot machinery have replaced human workers [17]. Converting shop-floor systems to cater for wind turbines was the subject of a conceptual study and included climbing bolt robots and temporary bolting arms.

The use of an Automated Bolting System (ABS) during seafastening was conceptualised by the authors and is shown in Figure 2. Fundamentally, the idea is that if the ABS is positioned in a recess underneath the grillage it could be mounted on a sled which can move between the individual flanges. The advantage of this is that one ABS can be used on the ship and will not require lifting and assembling, as it would to connect tower sections.

Since this work was conducted, a new technology has come on the market from Fistuca called BLUE Wedge which can accomplish both seafastening and a connection technique [18].

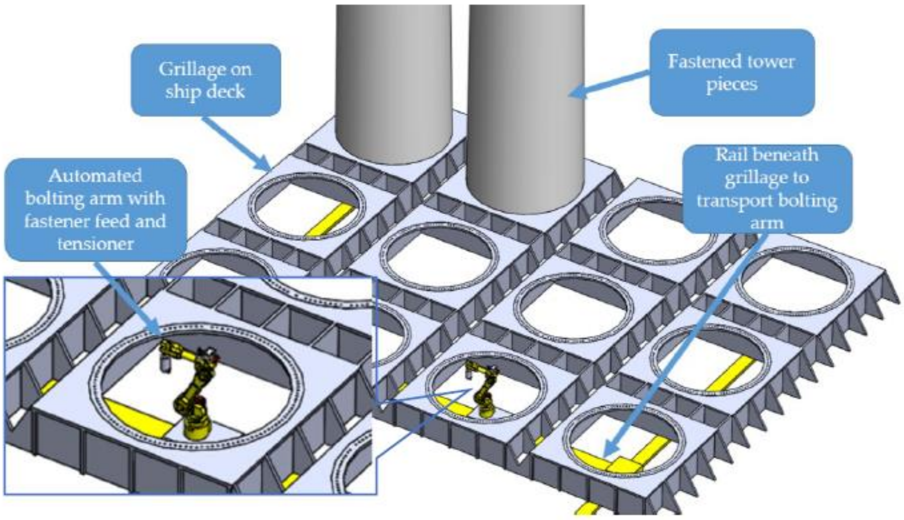


Figure 2. Automated bolted seafastening, concept illustration.

2.3. Assembly

The different offshore pre-assembly transportation and installation methods are the major driving force for a successful wind farm installation [19]. However, as outlined earlier in this paper, human presence beneath heavy lifts is the current procedure and the most hazardous aspect of offshore wind turbine installation operations.

Installation of pre-assembled concepts can be applied as a positive path towards achieving human-free lifting operations offshore, thereby minimising the number of lifts and reducing human exposure to lifting hazards. Pre-assembly, as well as assembly transportation and installation solutions are considered in this section.

Some of the conventional assembly and pre-assembly installation methods of bottom-fixed offshore wind turbines on already installed foundations are shown in Figure 3.

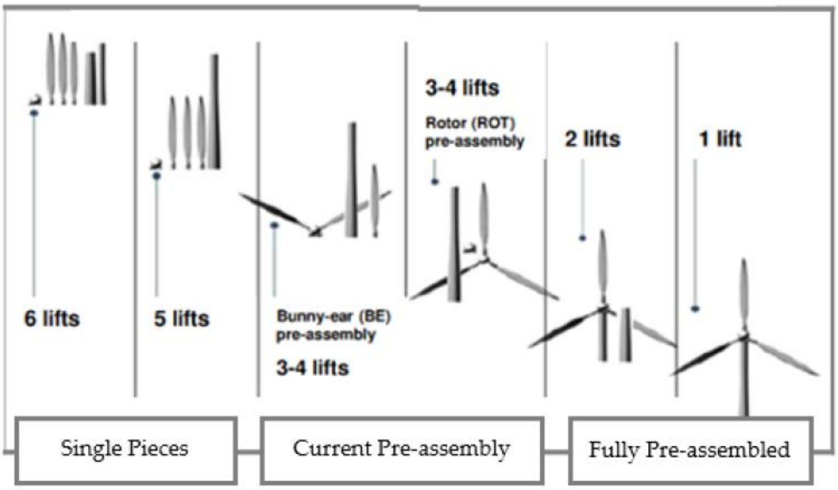


Figure 3. Offshore wind turbine current and proposed installation methods. Adapted from [20].

The turbine system can be transported offshore and installed in:

- Six lifting operations, transporting the turbine in single pieces (SP) [21], with the tower being split into two tower elements (2T), pre-assembling only the hub on the nacelle, and lifting each component separately. This solution can be employed where limitations in the design/operating capacity of equipment, or the stability of the installation unit (either vessel or barge) do not allow the entire tower (1T) to be lifted and transported.
- Five lifting operations performed in the same way as the six-lifts method but without splitting the tower into two tower elements.
- From four to three lifting operations, such as for bunny-ear (BE) and rotor (ROT) pre-assembly methods.
- From two to a single lifting operation.

One thing is clear: the fewer lifts, the fewer human exposures to hazards. However, the installation of turbines must also remain cost-effective. Thus, possible use of alternative configurations for safety reasons must be balanced against the cost of installation. Therefore, different pre-assembly configurations and some self-erecting concepts are compared in the MCDA. However, safety of transporting single pieces can be improved: it has been found that when installing single blades, the critical motion radius can be reduced by up to 30% through the use of tuned mass dampers [22]. With regard to floating wind turbines, their placement on site differs in terms of their transportation, which is dependent on the specific concepts (semi-submersible, tension-leg platform (TLP) and spar substructures [23]). Vertical transportation of buoyancy- and mooring-stabilised platforms, such as 'WindFloat' [24] and that suggested in [25], have already been employed commercially for a demonstration project. On the other hand, ballast-stabilised designs can either be transported vertically (assembling the tower on the floater section in situ [26]) or horizontally, as proposed by the 'WindFlip' concept [27]. To elaborate on what is meant by the 'current pre-assembly' method, Table 2 shows examples of how many lifts have been performed per turbine for several North Sea wind farms.

Table 2. North Sea installation characteristics, adapted from [28–30].

Project	MW Class	No. Turbine in the Farm	No. Units to Install	Duration (Days)	Method	No. Lifts per Turb.
Horns Rev.1	2	80	2	110	BE-1T	3
Prinses Amalia	2	60	2	330 *	BE-1T	3
North Hoyle	2	30	2	90	BE-2T	4
Nysted	2.3	72	1	78	ROT-2T	4
Lillgrund	2.3	48	1	73	ROT-2T	4
OWEZ	3	36	1	67	BE-2T	4
Thanet	3	100	1	197	SP-1T	5
Greater Gabbard	3.6	140	2	515 *	SP-2T	6
Lynn & Inner Dowsing	3.6	54	1	122	SP-2T	6
Thornton Bank I	5	6	2	70 *	ROT-2T **	6

* Approximatively derived days from data available online [28]. The exact dates from the first to the last turbine erection involve also working breaks for foundation installation, weather window availability and unplanned issues.

** Tower(s) and nacelle components separately pre-installed with respect to the rotor pre-assembly.

2.4. Concept Summary

Table 3 summarises all concepts considered, ordered into their respective categories. For more detail on each item, a reference is given where possible next to their name in the table.

Table 3. List of options compared in initial stage MCDA.

Guidance	Connections	Lifting Methods
Remote Control [31,32]	Bolting robot arm [17,34,35]	Offshore Assembly, Single Pieces [30]
Tag lines/Tag line Winches [33]	Hydraulic Seafastening [36,37]	Current pre-assembly [30]
High Wind—Boom Lock [13,33]	Internal Jack Seafastening [38]	Bottom Fixed, Partially Self-Erecting Wind Turbines (WTs) [39,40]
Funnels/Cones [4]	Friction Connection [16]	Bottom Fixed, Fully Self Erecting WTs
Multiple Cameras	External Climbing Bolt Robot	Bottom Fixed, Fully pre-Assembled Transportation [41,42]
Fish Eye lens	ConXtech Connection [39]	Floating WTs, Vertical Transportation [24,25]
Lasers, Distance Measurement	Bolt Conveyor	Floating WTs, Horizontal Transportation [43]
	Rotating Joint	
	Single, Large Thread	

3. Multi-Criteria Framework for Assessment of Human-Free Offshore Lifting Solutions

3.1. Introduction to MCDA

Numerous ideas are presented in this work, all of which aim to reduce the exposure to risk for workers during operations. The selection of the optimum solution, however, cannot simply be based on intuition or a single criterion. A fully automated crane system, which can position blades into the hub without any human intervention, would eliminate the risk but it would also be costly to develop and has limited application in offshore conditions to date due to operational environment requirements. This constitutes a multi-dimensional problem lending itself to MCDA. MCDA divides a decision into smaller parts, analyzing each and then combining through a logical process to present an aggregated performance outcome.

MCDA methods can be applied to any decision with complexity and have been employed in the sustainable energy industry as a whole [44], and within the offshore wind sector [45].

In the state of the art regarding MCDA within the renewable energy industry, Kolios et al. [46] discussed using a stochastic input with a variety of methods including TOPSIS. MCDA is also widely applied in the renewable energy sector [45,47–50]. Authors outside of renewable energy have found stochastic MCDA useful, particularly when limited preference information is available [51,52]. Further research regarding the TOPSIS method is discussed in Section 3.3. The general process for an MCDA is shown in Figure 4.

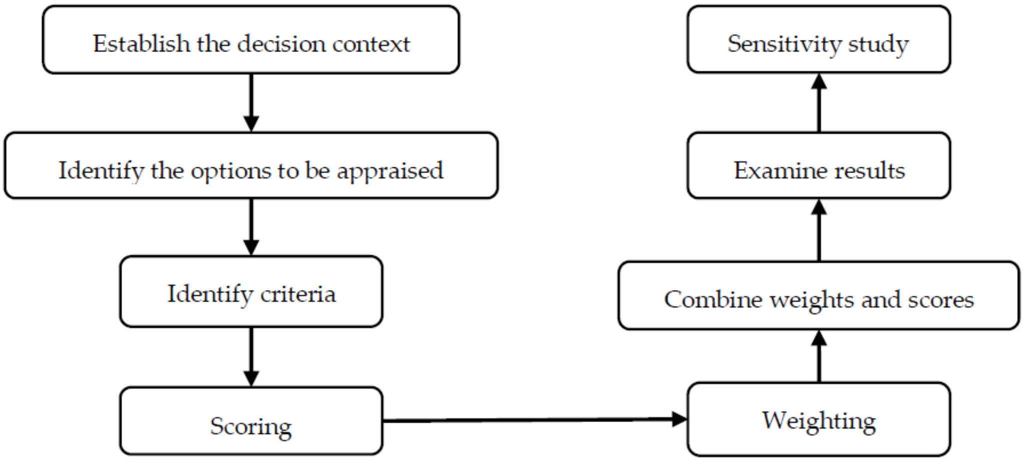


Figure 4. Process of an MCDA.

3.2. Methodology

The work involved a literature review and market search for existing technologies for reducing the human element in areas of high risk during lifting operations across industries. These included tools currently in use in industry, as well as new and conceptual designs proposed by the authors. Technologies were separated into three areas: guiding and control, connections, and assembly. Examples of these have been discussed in Section 2.

The methodology employed followed a structured path intended to make the best use of industry partners and maximise the effectiveness of the time and resources available and, finally, to produce a ranked list of options. The method is shown diagrammatically in Figure 5. The first step was to discuss the challenge with industry partners and assess incident data from offshore wind to determine what specific issues were faced and define the key areas of technology to be investigated. The next stage was to conduct a review of literature investigating potential technologies which either are designed for use in offshore wind or could potentially be applicable to offshore wind. At the same time, a survey was disseminated to those in the offshore wind industry through the industry partners with the aim of determining weights of the importance for a list of relevant criteria. The results from these last two steps were fed into the first stage of TOPSIS analysis as a method of filtering out 'bad' concepts and identifying promising concepts. After the first stage of TOPSIS, further study was conducted on the promising concepts, including an experiment testing guidance and control technologies. The purpose of this further research step was to obtain better data on the performance and applicability of the technologies for the intended purpose. This improved data was finally fed into a second stage TOPSIS analysis in order to produce a ranked list of the most promising technologies for those wishing to develop further and employ a human-free lifting solution for offshore wind. The important distinction of this method is that the literature review and the TOPSIS analysis (green and orange respectively in Figure 5) are performed twice.

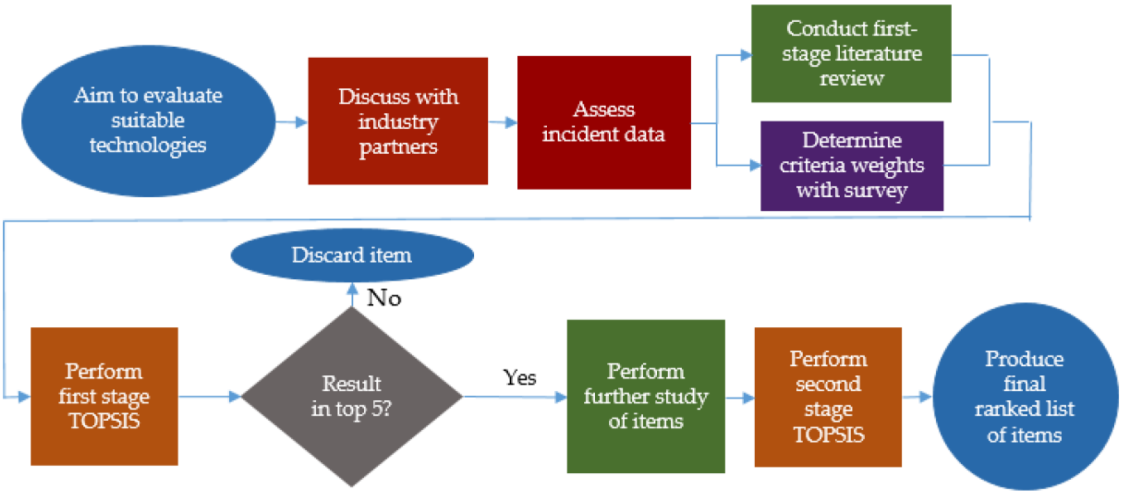


Figure 5. Flowchart outlining methodology employed in this work.

3.3. TOPSIS

There are numerous forms of MCDA; however, the 'TOPSIS' method was chosen to be used. The reason for this is that it is a straight-forward method that decouples the decision matrix from the weight vector and allows a combination of qualitative and quantitative criteria to be included in the analysis. It has also been utilised heavily for renewable energy problems, as summarised in [47].

The TOPSIS method was presented by Hwang and Yoon in 1981 [53]. TOPSIS is a simple method which utilises concepts of theoretical ideal positive and negative solutions and ranks alternatives by their Euclidian distance to these solutions [49].

The TOPSIS method is explained in references [47,54–56] but will also be presented here for reference with the following steps, which were applied using the criteria weighting and satisfaction values using a MATLAB (2015a, MathWorks, Natick, MA, USA) code:

1. A decision matrix is created holding the values for how well each alternative technology m satisfies each criterion n.
2. The decision matrix is normalised by dividing each value by the square root of the sum of all values in the matrix squared, as shown in the following equation:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\Sigma x_{kj^2}}} \tag{1}$$

   where r_{ij} is the weighted value in the decision matrix at point (i,j) and x_{kj} is the original value at that point.
3. The decision matrix is weighted by multiplying each value in the matrix by the criterion's corresponding weighting, as in the following equation:

$$v_{ij} = w_i \times r_{ij} \tag{2}$$

where v_{ij} is the weighted, normalised value and w_i is the weight value for that criterion.

4. A Positive Ideal Solution (IPS) and a Negative Ideal Solution (NIS) are created from the decision matrix. The PIS is the maximum of all of the 'good' criteria which the decisionmaker wants to maximise, and the minimum of all the 'bad' criteria. The NIS is the converse of this. These solutions are purely theoretical and are used only for comparison.
5. For each alternative, the geometric distance to the PIS and to the NIS, respectively, is determined. This is shown simply in the following equations:

$$D_j^{PIS} = \sqrt{\sum_{i=1}^{n}(v_{ij} - v_{ij}^{PIS})^2} \tag{3}$$

$$D_j^{NIS} = \sqrt{\sum_{i=1}^{n}(v_{ij} - v_{ij}^{NIS})^2} \tag{4}$$

   where D_j^{PIS} is the distance of the j^{th} alternative to the PIS, D_j^{NIS} is the distance of the j^{th} alternative to the NIS, and v_{ij}^{PIS} and v_{ij}^{NIS} are the weighted, normalised values of the ij^{th} criterion for the PIS and NIS respectively.
6. How close each alternative is to the PIS relative to the NIS, is evaluated with the following equation:

$$C_j = \frac{D_j^{NIS}}{D_j^{PIS} + D_j^{NIS}} \tag{5}$$

   By using this closeness value C_j, which can have values in the range from 0 to 1, the alternatives can finally be ranked. The closer the alternative is to 1 the better the alternative and the higher it is ranked.

3.4. Stochastic Expansion of TOPSIS

The TOPSIS method can be performed in a stochastic manner through the use of a Monte-Carlo method. In this way, weight values are randomly sampled from their respective fitted probability distribution. This process is repeated several times; in the case of this work, 100,000 iterations were performed. Through this repeated analysis the result is a range of values where the ranking can be different for each iteration. In this paper the mode rank is the primary value for comparison, but the mean C value is also presented as a comparison to the deterministic C value and deterministic ranking. The mode rank of an alternative is the rank which occurs most frequently in all of the iterations for that alternative.

3.5. Industry Survey and Decision Matrix

3.5.1. Industry Survey

A survey was sent out through G+ and other company contacts via a link to an online survey and all information entered by respondents has been kept anonymous. A series of problem specific and contextual questions were included in order to capture the background of the respondent for future correlation to their responses. In total, there were 38 respondents from industry with an average of 10 years' relevant experience. In the survey the respondents were asked to provide their job title, years of experience, and their perceived level of expertise in the field; the target respondent would have any range of practical experience in offshore wind lifting operations. Ultimately, a bias towards (Health, Safety and Environment) HSE managers and managers in general was noticed; this is probably due to the network in which the link was shared, but which in general is more informed on the subject matter, hence adding value to the results. Both perceived experience and number of years have been used to weight the results, which is discussed further in Section 4.2.1. Next, the respondents were asked to weight each of the criteria discussed in Section 4.2 from 1–9 (1 being not important and 9 being extremely important). There was also an option to include any criterion that, in the respondent's opinion, was omitted from the survey and any general comments.

Firstly, there seemed to be an overriding theme that removing the human from beneath the load, rather than simply reducing occurrence, was important and that if the appropriate practice could be determined, cost would not be an issue, particularly as there is a legal requirement to do so 'when practicable'. Secondly, this practice should be simple and reliable. There seemed to be some frustration with equipment complexity and that the complex equipment can be a burden to maintain. There was a desire for equipment which had a wider weather window and 'foolproof' use.

3.5.2. Response Robustness

Any analysis method is only going to be as good as its data input; therefore, it is important to have confidence in the values obtained from the survey. A great deal of attention was paid to ensuring the quality of responses. The survey was only shared in specialist circles, a link was shared on LinkedIn by an industry contact in G+ and was also shared on the G+ website, and this made it unlikely that anyone not related to this field would see it.

Each response was checked individually to ensure no abnormalities, i.e., a repeated series of the same number or missing data. It should be noted that, for all 38 responses used, they had answered the survey fully. More than 38 responses were received, but some only answered the first half of the questions, so their responses were not included because it was felt that they were not fully committed to the survey. Two of the 38 respondents had less than 3 years of experience (0.33 and 2 years), but if their responses were removed it would had very little impact on the result; the average change in criterion weight was 0.83%, and the highest change was only 2.66% for that particular criterion weight.

The average years of relevant offshore lifting experience for all of the 38 industry respondents was 9.9 years and had a maximum of 25 years. This indicates that the survey response is informed by a great deal of experience and that those who responded are representative of those within the industry who make the decisions. Anecdotally, the figures given by the respondent with the least experience did not differ significantly from the mean response; this indicates that using a minimum years' experience requirement would not necessarily have improved the result.

4. Industry Survey and Application

4.1. Criteria Identification

When considering implementing a new technology, the full timeline of developing and operating was reflected. Hence, the criteria were split into high-level groups of 'Research + Development', 'Operational', 'Manufacturing', and 'Other'. 'Research + Development' covers variables to implementation of the technology, 'Operational' defines important criteria during use, and 'Manufacturing' the attributes required to successfully produce the concept.

Each criterion can be seen in Figure 6 and is either positive or negative. For instance, when scoring an option on cost (negative variable) a lower value represents a more cost-effective option, i.e., cost of cameras 2, cost of self-erecting turbine 8, showing that the cost of installing cameras is less and therefore more viable. The process for scoring these criteria, in terms of weight, and scoring the technologies in terms of 'Criteria Satisfaction' are discussed in Section 4.2. The criteria presented were subject to group discussions to investigate completeness, redundancy, and, importantly, mutual independence. Independent criteria are such that the score of one criterion does not affect another. At an extreme this poses the risk of 'double counting' which skews the decision matrix by adding weight to a property that has been split into categories that are intrinsically linked. The criteria chosen and their respective categories are shown in Figure 6.

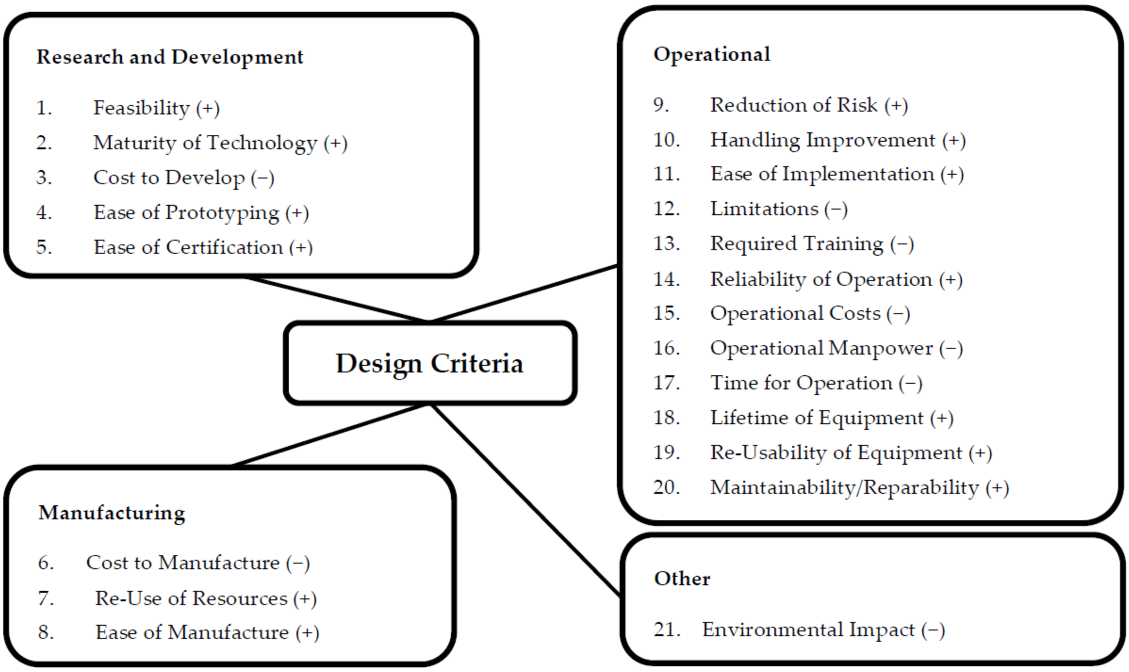


Figure 6. Criteria to be considered (+/◎ indicate positive/negative variables).

4.2. Scoring

4.2.1. Criteria Weights

The weight values used for each criterion were the averages of the values given by respondents to the survey. As part of the survey, the number of years of relevant experience as well as the perceived level of expertise were requested and used to weight the value of the response. Figures 7 and 8 show the averaged responses from the survey which were used as weights for the deterministic MCDA. The blue bars are the averages of all of the responses while the orange and grey bars are weighted by perceived level of experience and by years of experience respectively. While these years' experience and perceived level of experience weights have some effect on the final values, it is minor. In this instance there is no significant correlation between experience by either measure and perceived level of importance of each criterion. It is important to note that in this case a linear weighting is applied, meaning that each response is multiplied by its experience value and the sum is divided by the sum of the experience values. A more noticeable difference may be seen if the shape function of weighting were to be changed, such as that in [55], in which a square weighting model produces larger factors between expertise ratings.

Table 4 shows what the coefficients such as C1 refer to for each distribution in Table 5, which shows the distributions which best fit the response data. Distributions were fitted using Palisade @RISK and the distributions were chosen based on the Kolmogorov-Smirnov (K-S) goodness of fit index. Discrete distributions are presented, as the data set is discrete. However, in the stochastic analysis, which is described in Section 3.4., the continuous distributions were used as, in the TOPSIS analysis, there is no reason why the weight value must be an integer.

While items such as 'Reduction of Risk' had a very low standard deviation of 0.56, indicating good agreement by all respondents, other items had a significantly larger standard deviation, for instance 'Environmental Impact', as it can be seen in Table 5. The mean value for all standard deviations was 1.70.

Table 4. Coefficients referred to for each distribution in Table 5.

Distribution	'C1'	'C2'	'C3'
Binomial	Number of trials	Probability of success	-
Uniform	Minimum	Maximum	-
Poisson	Rate λ	-	-
Extreme Value	a	b	-
Normal	Mean	Standard deviation	-
Triangular	Minimum	Most likely	Maximum
Logistic	Mean α	Scale β	-

Table 5. Fitted distributions of weighting response data.

Criteria	Discrete Dist.	C1	C2	Continuous Dist.	C1	C2	C3
Feasibility	Binomial	10	0.78	Extreme value	8.47	0.98	-
Maturity of Tech	Binomial	11	0.54	Normal	5.97	1.73	-
Cost to Develop	Binomial	11	0.48	Normal	5.26	1.69	-
Ease of Prototyping	Uniform	1	8	Uniform	0.81	8.19	-
Ease of Certification	Uniform	2	9	Uniform	1.81	9.19	-
Handling Improvement	Binomial	9	0.89	Triangular	4.66	9	9
Cost of Manufacture	Binomial	12	0.47	Logistic	5.65	0.96	-
Ease of Manufacture	Binomial	11	0.46	Normal	5.85	1.48	-
Reuse of Resources	Uniform	2	8	Uniform	1.84	8.16	-
Environmental Impact	Uniform	1	9	Uniform	0.78	9.22	-
Reduction of Risk	Binomial	9	0.97	Triangular	6.87	9	9
Ease of Imp. and Op.	Binomial	9	0.85	Extreme Value	8.23	0.94	-
Limitations	Binomial	9	0.77	Logistic	7.06	0.81	-
Required Training	Poisson	5.58	-	Logistic	5.72	1.14	-
Reliability of Operation	Binomial	9	0.92	Triangular	4.86	9	9
Operational Costs	Binomial	12	0.52	Logistic	6.30	1.02	-
Operational Manpower	Poisson	5.58	-	Extreme Value	6.92	1.60	-
Time for Operation	Binomial	10	0.72	Extreme Value	6.92	1.60	-
Lifetime of Equipment	Binomial	11	0.54	Extreme Value	6.92	1.60	-
Reusability of Equipment	Binomial	11	0.54	Logistic	6.20	1.09	-
Maintainability/Reparability	Binomial	10	0.69	Extreme Value	6.92	1.60	-

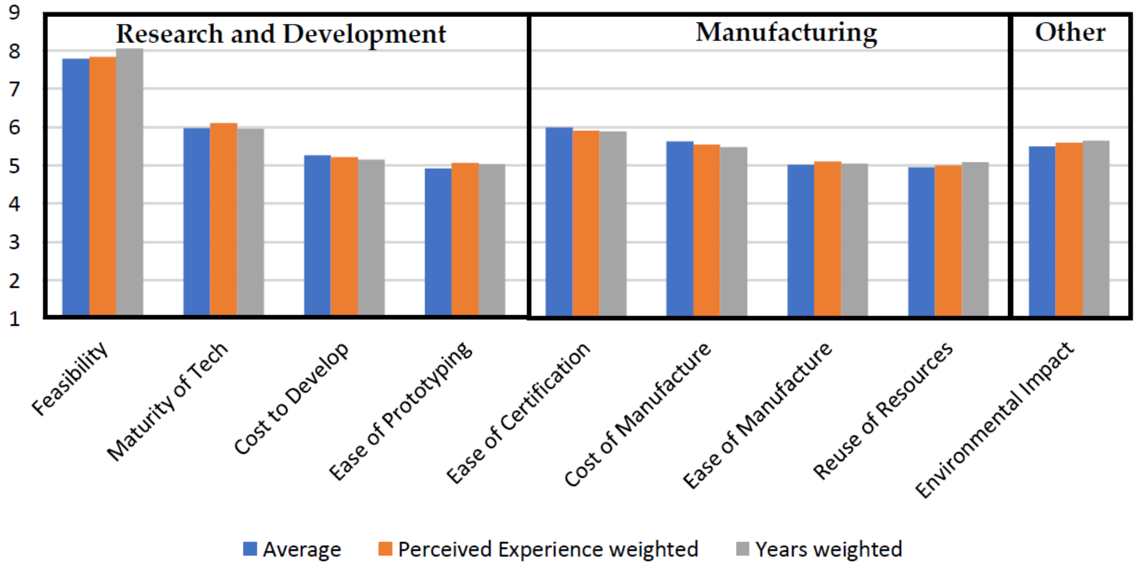


Figure 7. Averaged responses to the sections 'Research + Development', 'Manufacturing' and 'Other'.

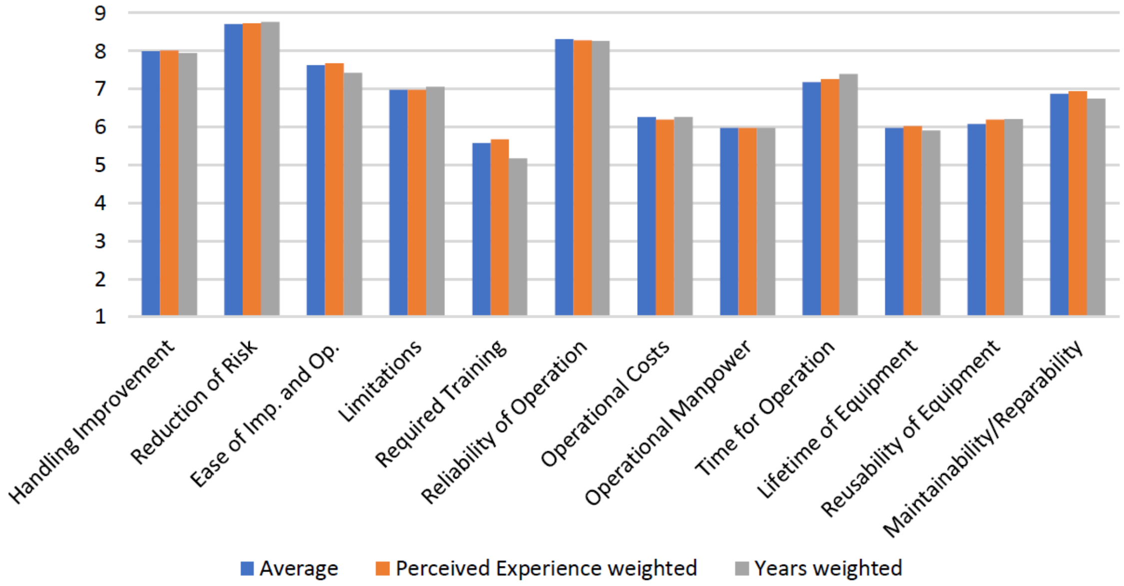


Figure 8. Averaged responses to the section 'Operational'.

4.2.2. Decision Matrix

One of the most challenging parts of this multi-criteria analysis is the determination of how well each alternative satisfies the criterion. If the technology is at a comparatively mature level of development, for example wind turbine support structures, then an empirical or quantitative method can be used to determine criteria satisfaction, as was the case in [46]. However, the technologies investigated in this study are not mature and, particularly in the initial stage of investigation, it may even be unclear what exactly the system or combination of systems consists of. Additionally, the technologies cover a broad range and are fundamentally very disparate. While an empirical method may be suitable to determine criteria satisfaction for one technology, the method may not be suitable for another and an alternative method may not be comparable. The actual numbers are not comparable if the technologies accomplish very different tasks; for example, one technology may cost significantly more than another but if it accomplishes a very different task it may be better value for what it does.

The criteria satisfaction was based on qualitative judgement as this is the only method that could be used for all categories. At the initial stage, the authors evaluated the technologies that they had respectively researched as they would be best placed to make that judgement. The Likert scale [56] was used, giving scores from 1 to 9 for each criterion to evaluate how well, or to what extent, that criterion was satisfied. The different sections were not compared to each other at this stage as the judgements of individuals are not comparable.

In the final stage, the authors scored all the technologies presented and these values were averaged. This was performed after a final presentation to ensure that everyone had an understanding of each other's sections. The average value was used to produce the final ranking; the decision matrix of this final stage.

Table 6. Second stage Decision Matrix, averaged values. (Category numbers 1–21 as in Figure 6).

Concepts	R & D					Man.			Operational												Oth.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Boom Lock and tag lines	9	8	2	8	7	4	7	7	6	6	6	3	4	5	3	4	5	6	8	7	2
Camera system + mech. guidance	7	5	5	7	6	5	6	6	8	7	8	5	5	7	4	4	3	4	7	6	3
Robot arm for seafastening	8	7	6	5	6	6	5	7	7	8	7	4	5	6	5	3	4	7	8	8	3
Boom Lock, tag lines, cameras + mech. guidance	8	6	6	6	6	6	7	6	9	8	7	4	7	8	6	4	3	5	7	6	4
Current pre-assembly practice	7	7	3	7	7	3	8	7	5	6	7	6	4	7	5	4	5	7	7	6	3
Camera system (3 × fine tune, 1 × 360, + redundancy)	7	7	4	7	6	2	7	7	6	6	5	4	6	5	2	4	6	5	7	6	2
Robot arm for bolting during construction	7	6	7	5	6	6	5	6	7	7	6	5	4	7	5	3	4	7	8	8	3
Completely hydraulic seafastening	7	6	5	5	6	6	4	6	7	7	6	5	4	6	4	3	4	6	7	6	4
Offshore Assembly (single pieces) installation	9	9	1	8	8	2	8	7	2	4	7	4	3	8	4	5	7	7	7	6	4
Partially hydraulic seafastening	8	8	4	7	7	4	4	7	5	6	7	4	4	6	3	6	7	6	8	6	3
Bottom fixed WTS (Fully pre-assemb. transportation)	4	4	6	5	4	8	4	5	7	7	5	7	7	5	9	4	2	7	6	6	5
Bottom fixed WTS (Partially self-erecting)	4	3	8	5	3	7	3	4	4	6	4	7	6	4	6	5	5	6	5	6	5

This method of evaluation was deemed sufficient not only due to the inherent limitations but also in light of the objective of the MCDA. Initially, the MCDA was used to streamline options for further study; this was important so that the limited time available could be spent more efficiently and thoroughly, evaluating the ideas at this stage would be counter to that. The second stage was to provide a recommendation to industry for future development. The method used for the final stage was not entirely different from the method used to elicit criteria weightings—those knowledgeable on the subject were asked. For the early nature of this work, it was decided that this was sufficient to accomplish the intended aims.

4.2.3. Stochastic MCDA

The shape of distribution of the responses varied between the different criteria. Based on analysis of the response data using the @RISK extension of Excel from Palisade [57], the response distributions fit to five different probability distribution functions: Normal, Uniform, Triangular, Logistic, and Extreme Value; the distribution used for each criterion was chosen based on the goodness-of-fit parameters calculated by @RISK using the Kolmogorov-Smirnov index. This variation is demonstrated in the histograms shown in Figure 9a–d, their relative distribution is stated in the figure caption and the distributions of other criteria, including their coefficient values, are given in Table 5. This is supported by the approach used by Kolios et al. [47], where Monte Carlo (MC) simulation was used to perform the analysis and evaluate confidence in the output. An MC approach was also used in this study and will be compared with a deterministic approach to the same case. The stochastic expansion process is shown diagrammatically in Figure 10.

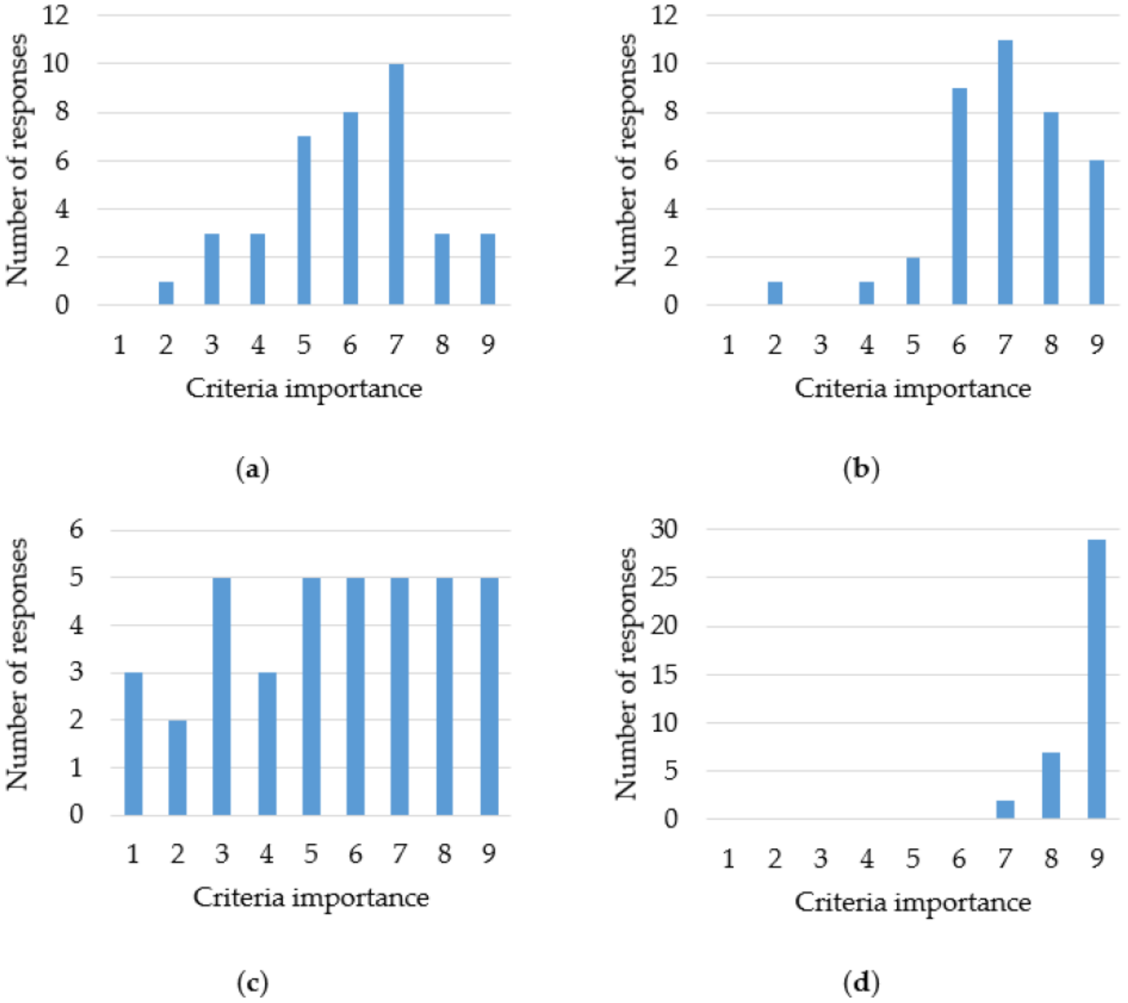


Figure 9. Probability distribution of responses for various criteria: (**a**) Maturity of technology, fit to a Normal distribution; (**b**) Limitations, fit to a Logistic distribution; (**c**) Environmental impact, fit to a Uniform distribution (**d**) Reduction of risk, fit to a Triangular distribution.

To perform the MC analysis in this study, 100,000 TOPSIS iterations were conducted, each time using weight values randomly generated from the alternative's respective continuous probability density function (PDF) shown in table 5. A check was performed so that if the randomly generated value was either less than 1 or greater than 9, a new value would be generated for that iteration, ensuring that all weight values were within the defined limit. TOPSIS C values and ranking of the alternatives are determined for each iteration. The mode rank for each alternative is then determined as well as for how many iterations the alternative rank is equal to its mode rank, as a percentage of the total number of iterations. The average C value (C_{avg}) and the standard deviation as a percentage of the alternative's C_{avg} are also presented. Finally, a deterministic TOPSIS is performed using mean response values for comparison, calculating TOPSIS C values for each alternative and the alternative's rank.

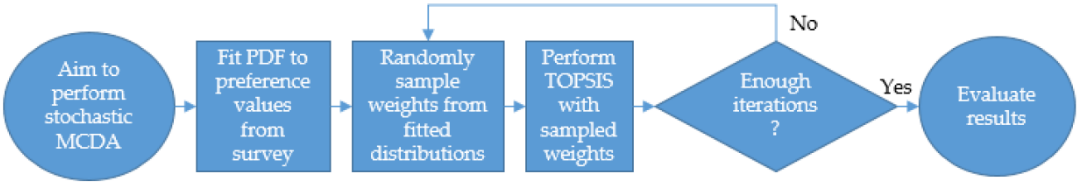


Figure 10. Process to stochastically expand MCDA.

5. Results and Discussion

5.1. Results

5.1.1. Stage 1—Streamlining Within Categories

Tables 7–9 show the top 50% of results from all of the ideas per category. These results can be compared within each table but cannot be compared between different tables due to the fact that the criteria satisfaction values were determined by different individuals and that they are separate TOPSIS analyses. Scaling of the values in each analysis on the normalisation stage is influenced by extreme values, so similar values between tables do not represent similar suitability.

Table 7 shows the results from the guidance and control section. Existing ideas such as guide pins and Boom Lock perform well due to the confidence in these comparatively simple ideas. Camera systems are at the bottom of these top ideas, possibly due to the uncertainty at this stage.

Table 8 shows the results from connections and seafastening. The top idea is automation of the bolting procedure followed by two novel seafastening methods and finally a new connection type.

Table 9 shows the initial results for the assembly section. Current pre-assembly methods, for example 'bunny ear' method, rank top followed by two full pre-assembly methods and finally the conventional method of constructing individual pieces at the site.

This initial analysis served as a guide to the research team rather than a fixed prescription, therefore the concepts chosen for each individual section may differ from those presented here.

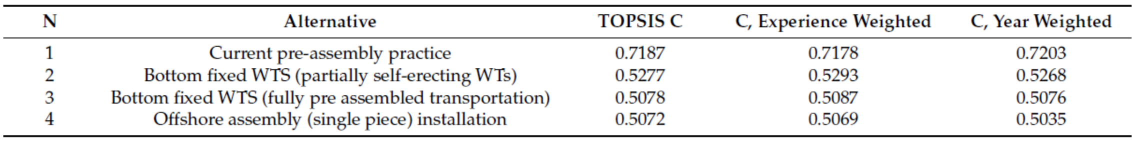
Table 7. First stage TOPSIS results for 'Guidance and Control'.

N	Alternative	TOPSIS C	C, Experience Weighted	C, Year Weighted
1	Guide Pins	0.7124	0.7108	0.7126
2	Remote Control	0.7099	0.7097	0.7077
3	Tag lines/Tag line winches	0.6668	0.6681	0.6694
4	High Wind + Boom Lock	0.6389	0.6409	0.64
5	Funnels/Cones	0.6318	0.6307	0.6297
6	Multiple Cameras	0.6268	0.6257	0.6299

Table 8. First stage TOPSIS results for 'Connections and Seafastening'.

Table 9. First stage TOPSIS results for 'Assembly Methods'.

N	Alternative	TOPSIS C	C, Experience Weighted	C, Year Weighted
1	Bolting robot arm	0.6475	0.6495	0.6489
2	Hydraulic Seafastening	0.6125	0.6127	0.614
3	Internal Jack Seafastening	0.6125	0.6127	0.614
4	Friction connection	0.5647	0.5645	0.5631



N	Alternative	TOPSIS C	C, Experience Weighted	C, Year Weighted
1	Current pre-assembly practice	0.7187	0.7178	0.7203
2	Bottom fixed WTS (partially self-erecting WTs)	0.5277	0.5293	0.5268
3	Bottom fixed WTS (fully pre assembled transportation)	0.5078	0.5087	0.5076
4	Offshore assembly (single piece) installation	0.5072	0.5069	0.5035

5.1.2. Stage 2—Global Ranking

Further development of prospective technologies including experimental, design, and computational work was undertaken between stages 1 and 2. Final proposed ideas or suites of ideas developed in each section are compared directly to draw overall priorities and are presented in Table 10. The top five recommendations based on the final stage stochastic analysis are:

- Boom Lock and tag lines
- Automated bolt installation/fastening used for seafastening
- Camera system with mechanical guidance
- Current pre-assembly practice of partially assembled components carried to the site for installation
- Boom Lock, tag lines, mechanical guidance and cameras

The results in Table 10 show that, by considering the analysis stochastically, the rank can change significantly for some of the alternatives. This suggests that, given a variety of distribution types, using the mean weight is not always appropriate. However, using the mean C value to rank the alternatives, rather than the mode rank, the rank of alternatives would again change slightly. The mode rank is simply the rank which occurs most frequently for the alternative.

Table 10. Final ranking of all proposed ideas.

Concept	Deterministic		Stochastic				
Technology	Rank	C	Rank	Mode Rank	% Occ. of Mode	Mean C	Standard Deviation of C
Boom Lock and tag lines	1	0.673	1	1	99	0.680	2.12
Robot arm for seafastening	3	0.616	2	2	32.7	0.610	3.28
Camera system (3 × fine tune, 1 × 360, + redundancy)	6	0.589	3	2	24.4	0.600	3.98
Camera system + mechanical guidance	2	0.617	4	3	32.8	0.609	2.69
Current pre-assembly practice	5	0.592	5	5	24.4	0.603	2.21
Boom Lock, tag lines, mechanical guidance and cameras	4	0.599	6	6	28.0	0.584	3.95
Robot arm for bolting during construction	7	0.565	7	7	23.6	0.559	3.59
Completely hydraulic seafastening	8	0.556	8	8	30.2	0.553	2.87
Offshore Assembly (single pieces) installation	9	0.546	9	9	21.4	0.561	4.26
Partially hydraulic seafastening	10	0.545	10	10	34.6	0.550	3.98
Bottom fixed WTS (fully pre-assembled transportation)	11	0.390	11	11	100.0	0.371	7.21
Bottom fixed WTs (partially self-erecting)	12	0.236	12	12	100.0	0.229	6.46

5.2. Discussion

There are three main areas where this work is useful and provides insights: the collation of useful technologies, survey results from industry, and the stochastic MCDA process.

The concepts discovered in the process are important for the industry. Some of these concepts, such as the robotic arm for seafastening, are currently a long way from being implemented, but others, such as the use of cameras and physical guidance, could be implemented potentially in the near future. The end output from this method is both a broad review of technologies with an in-depth review of highly ranked technologies. The authors hope that this work can help lead to a reduction in significant offshore wind heavy lifting incidents.

The results from the industry survey are both useful for this work, but also potentially useful for other work in the future. The survey results show that there is little disagreement that reduction of risk is extremely important but it also shows that it is not the only important value. The next three highest criteria were 'reliability of operation', 'handling improvement' and 'feasibility'. The cost to develop the technology and how easy it is to manufacture seemed relatively unimportant, but not negligible. This shows a strong desire in offshore wind to improve the safety of offshore lifting operations. One should bear in mind, however, that this survey was conducted specifically in the context of technologies intended to improve the health and safety in offshore wind heavy lifting operations and that applying the findings outside of this context may not be valid.

Typically, MCDA analyses are applied in a single stage; however, in this work the TOPSIS method was applied in two stages. This method allowed for a more efficient use of resources when conducting the work and potentially resulted in producing a more useful list of technologies. There were some challenges in applying this approach. One challenge was that some technologies only had a limited amount of information available for them and if most of the sources were discovered in the first stage then there is little new information on them in the second stage. Conversely, if significant new information is discovered on a technology in the second stage, making it more or less favourable, then the question has to be asked if the first stage was really accurate and should it have been repeated. While both concerns are valid, in the first case the implications are not significant and in the second they can be dealt with. Overall the method of applying an MCDA in two stages appears to work well for this kind of work where the first stage is used to guide the application of resources as more information is gathered.

The outcome of the second stage MCDA illustrates that Boom Lock and tag lines are the most promising concepts to be taken forward. This seems reasonable as both aspects are fully developed products such that their technology readiness level is high, and when combined they provide a less risky and cost-effective solution to the problem. It should be noted that there are some limitations to these results, most notably subjective and qualitative scoring of the concepts within each category.

6. Conclusions

This paper presents a framework for deciding upon the most suitable solution to health and safety problems and has described a selection of concepts for human-free offshore lifting operations when installing wind farms. Concepts have been explored with a view to reducing the need for people to be beneath suspended loads and thus improve the safety of the operations. Safety, though, is not the only criterion to consider when introducing new technologies to an industry. For this reason, a multi-criteria decision analysis method was used to evaluate concepts aiming to better inform future decisions but also to give a final recommendation for further development. A survey was distributed to industry personnel contacts with relevant experience and was used to elicit weighting values for use in the MCDA. The results of the survey showed not only which criteria were most important but also how opinion varied across the industry on some criteria as there was not always general agreement among respondents. Technologies were evaluated qualitatively in two stages for criteria satisfaction values. A summary of the ideas most worth developing has been presented. Based on the survey, criteria such as ‘reduction of risk’, ‘handling improvement’, and ‘reliability of operation’ were most important while ‘ease of manufacture’, ‘required training’, and ‘reuse of resources’ were less important. The most highly recommended concepts are:

1. Boom Lock and tag lines—These are control elements which improve handling and reduce risk by providing more contact with the load at key points.

2. Camera system and mechanical guidance—These give guidance as well as a level of fine control without which it would have required operators to be physically present.
3. Robot arm for seafastening—This concept was proposed by the authors and consists of a robot bolting system, a concept used in shop floor construction, for completing the seafastening operation.
4. Boom Lock, tag lines, mechanical guidance, and cameras—This is a combination of the first two recommendations. It is lower than both recommendations because using both increases complexity and difficulty in implementation, as well as cost.
5. Current pre-assembly practice—This is as opposed to either the 'single pieces' or 'fully pre-assembled' methods discussed in Section 2.3. However, it has to be kept in mind that other pre-assembly methods can have advantages in the right circumstances.

While some of the recommended concepts still need to be developed further, the realisation of other concepts, such as the use of cameras and physical guidance, is expected to be feasible already quite soon. Thus, this work should contribute to making lifting operations in the offshore wind industry safer. Besides the focus on health and safety, the conducted survey in this work also showed that reliability, ease of handling, and feasibility of new technologies are of high relevance for the offshore wind energy industry.

The decision analysis framework developed can be applied in similar future problems, and be further expanded in a more detailed analysis, by having a quantitative scoring scheme for the scoring of different decision alternatives against each of the selected criteria. Furthermore, the applied approach of a two stage TOPSIS analysis presented a new method—as a potential alternative to the typical single stage MCDA—with which resources can be used more efficiently and very valuable results can be obtained in the second stage due to the focused approach.

Author Contributions: M.R., T.B., P.C., D.C. and M.L. conceived the work and undertook literature reviews, experimental work and wrote various sections of this paper. T.B. set-up and sent out the survey and collated the paper. M.R. analyzed the data using the MCDA framework. A.K. and F.B. steered the work and gave invaluable advice.

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Annex C

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Human-free offshore lifting solutions

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Abstract. With single elements weighing up to hundreds of tonnes and lifted to heights of 100 meters, offshore wind turbines can pose risks to personnel, assets, and the environment during installation and maintenance interventions. To increase safety during offshore lifts, this study focuses on solutions for human-free lifting operations. Ideas in the categories of logistics, connections, as well as guidance and control, were discussed and ranked by means of a multi-criteria decision analysis. Based upon 38 survey responses weighting 21 predefined decision criteria, the most promising concepts were selected. Logistically, pre-assembled systems would reduce the number of lifts and thus reduce the risk. A MATLAB-based code has been developed to optimise installation time, lifted weight, and number of lifts. Automated bolting and seafastening solutions have high potential to increase safety during the transport of the wind turbine elements and, additionally, speed up the process. Finally, the wind turbine should be lifted on top of the support structure without having personnel being under the load. A multidirectional mechanical guiding element has been designed and tested successfully in combination with visual guidance by cameras in a small-scale experiment.

1. Introduction

Lifting operations in the offshore wind energy industry involves heavy loads in the order of hundreds of tonnes, as well as working heights of around 100 meters, all while the lifting operation is being subjected to the wind and wave conditions at sea. This makes offshore lifting operations and offshore wind turbine installations hazardous. Guidelines and standards for health and safety in lifting operations in general [1–4], as well as specific to the offshore environment [5–7], exist. Despite this, having people directly under the load for guiding and securing is still common practice in offshore wind turbine installations. G+ (formerly G9) [8] provided, in addition to the publicly availably annual incident reports [9–11], the full data for health and safety incidents occurring during offshore lifts from 2014 to the third quarter of 2016. From these reports the total number of incidents and dropped objects per hour of work is determined and shown in figure 1.

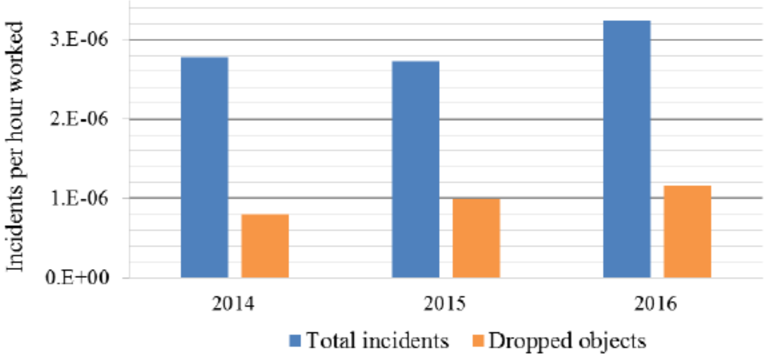


Figure 1. Total incidents and dropped objects per number of hours worked.

Whilst the number of incidents per number of hours worked decreased slightly from 2014 to 2015, it rose again in 2016. Over the same period, normalised incidents due to dropped objects increased year on year. Although small, these increases are important, especially as the installed capacity of offshore wind energy, and thus also the number of lifting operations performed each year are expected to grow significantly, based on the estimations by [12]. A recent study [13], matching safety indicators against the same G+ incident data, draws similar conclusions and the authors advise having safety indicators for dropped objects, particularly during lifting operations, as this is a crucial area for offshore health and safety incidents. The more details in the incident reports [9–11] on the statistics for the reasons, areas, and consequences for incidents substantiate as well the importance of safer and improved handling in offshore lifting operations.

Thus, the motivation for this study was to conduct research into methods and technologies that could reduce the need for personnel near lifting operations, and to assess their feasibility. Different concepts for human-free offshore lifting operations in the categories of assembly and logistics, connections and seafastening, as well as guidance and control, have been collated and investigated, mainly based on broad literature reviews and industry reports on current practices, but also based on patents for new designs and innovative solutions proposed by the authors. The broad range of concepts was assessed with respect to 21 predefined criteria and ranked by means of a multi-criteria decision analysis of 38 survey responses. More details on this analysis can be found in [14]. The concepts most worth developing were investigated in more detail and are presented in this work.

In the following, the most promising solutions are presented for the three categories: assembly and logistics (section 2), connections and seafastening (section 3), and guidance and control (section 4). A short summary of existing concepts precedes each section. At the end of this paper (section 5) the results are concluded.

2. Concepts for logistics and assembly solutions

Installation pre-assembly concepts can be applied as a positive path towards achieving human- free lifting operations offshore, minimizing the number of lifts and reducing the human exposure to lifting hazards. Existing transportation and installation methods are:

- the bunny-ear (BE) method for installation of the rotor in two lifts (figure 2a): first two blades attached to the nacelle are lifted on top of the tower, and then the third blade is connected to the wind turbine in a second lift;
- the rotor star (ROT) method for fully pre-assembled installation of the rotor (figure 2b): the nacelle is mounted in a separate lift on top of the tower and then the entire rotor-hub assembly is lifted as one unit;
- single piece installation (SP) of the rotor-nacelle assembly (RNA) (figure 2c): each blade is lifted individually, as well as the nacelle with pre-assembled hub;
- installation methods for the tower: the tower can be lifted as one piece (1T) or two sections (2T).

Combining the pre-assembly methods for RNA and tower, a wind turbine can be installed with three to six lifts. Installation is also possible in only one or two lifts if the tower section and RNA are fully pre-assembled.

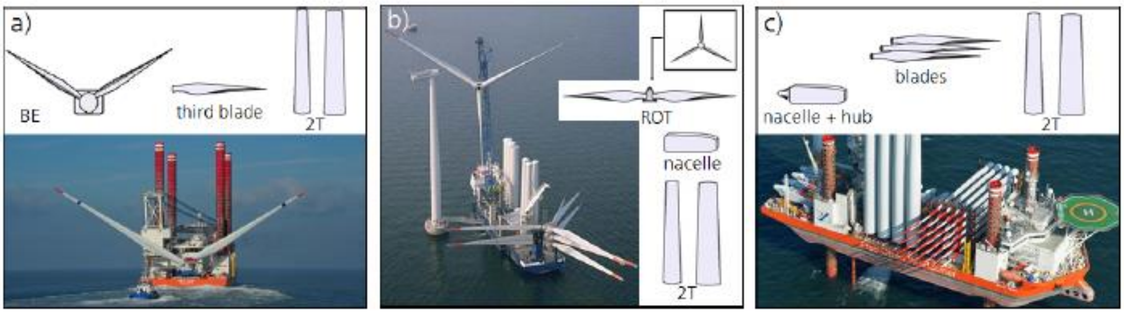


Figure 2. Pre-assembly methods: (a) Bunny-ear [15, 16], (b) Rotor star [15, 17], (c) Single pieces [15, 16].

Even if pre-assemblies of wind turbine components would require fewer lifts and thus reduce the number of hazardous offshore lifting situations, pre-assembled systems are heavier than single pieces and have larger wind exposed areas, which could actually increase the lifting hazards. Furthermore, vessel requirements, lifting capacities, and stability limitations for transportation and installation of pre-assemblies constrain the feasibility and advantages of this pre-assembly method. Thus, a good compromise between number of lifts and lifted weights has to be found.

For this purpose, a discrete-event simulation model of lifting operations for the installation of a wind farm is implemented in a MATLAB script file (m-file) and integrated into a graphical user interface, to allow a more user-friendly inclusion of the input data. Although the code has been developed for deterministic data input and output, as a future work, the time quantities could be integrated as random variables to model the system stochastically. Due to the coexistence of different criteria the program does not clearly outline the optimal practise but aims to offer an overview of pros and cons of the different transportation and installation methods.

Figure 3 presents a flow chart of the developed installation optimisation program. Based on data input for the turbine and the vessel, systems-fitting functions derive information on the vessel loading-condition, and the lifting-operation hazard for the previously described BE and ROT configurations, as well as traditional SP transportation. Additionally, special tower and blade transportation methods, such as gathering single blades in a cage and having the tower as one piece or split into two sections, are allowed. Transportation constraints, due to vessel limitations, have been integrated as well. Despite the possibility to include overboard limits, the orientation of the pre-assembly on the vessel (transverse or longitudinal for BE, as well as inside- or outside-pointed transportation for ROT), and other user specified positioning along the deck, simplifying assumptions have been made concerning the vessel's stability. Specifically, asymmetric loading is not allowed and the maximum allowed position of the vessel's centre of gravity cannot be checked. Furthermore, a time counter provides an estimate of the time it would take to install the turbines based on the specified configurations. This estimation, however, is affected by time variables which have to be assumed, such as the time to load components and pre-assemblies on the vessel. As it was also necessary to account for the effect of weather windows and vessel's availability, a time variable for the average working hours per day is defined.

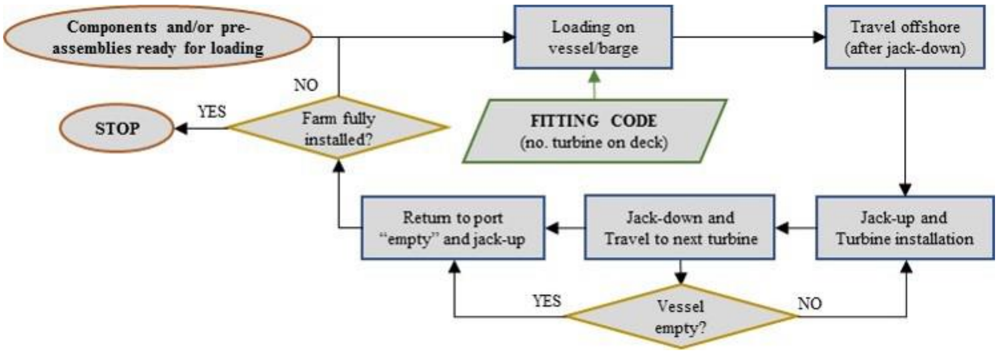


Figure 3. Installation pre-assembly MATLAB code flow chart.

At this preliminary stage, the program was validated against two real case studies: Thanet and OWEZ (Egmond aan Zee) wind farms. For the latter, three possible configurations, along with characteristic properties, are presented in figure 4. The 36 wind turbines of OWEZ wind farm were transported in a BE-2T configuration, starting from Ijmuiden port, and installed by the A2SEA Sea Power jack-up vessel within around 67 days [15, 18]. The assumed loading and offshore installation times for each component were taken from [19], while a sensitivity analysis has been performed on the working hour, as shown in figure 5. As expected, in general the SP transportation would have led to a considerable increase in installation time. Although, as verified by the simulations, the adopted BE-2T configuration has the highest time saving, a ROT solution could reduce the amount of the maximum weight lifted by the crane, with the same number of lifts and slightly increased time required to install (about 10 days).

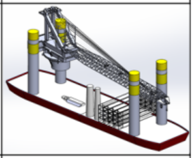
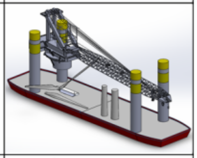
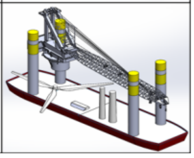
		Occupied area [m²]	Net load on deck [tons]	No. turbines per voyage	Total no. of lifts	Max. lifted load [tons]	Configuration visualization
SP-2T	4 blades in cage	1007	1339	5	216	88.0 (nacelle with hub)	
BE-2T	Transverse	969.1	535.6	2	144	101 (BE pre-assembly)	
ROT-2T	Inside-pointed	325.8	267.8	1		83.6 (upper tower element)	

Figure 4. Exemplary transportation possibilities for OWEZ wind farm case study.

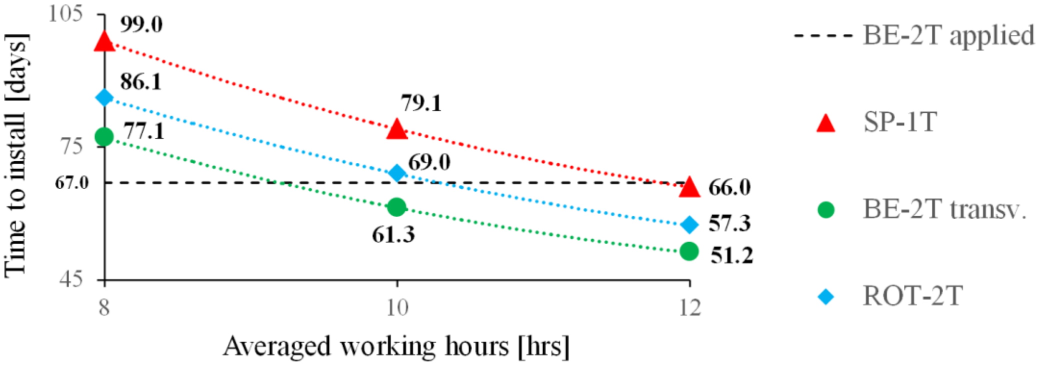


Figure 5. Sensitivity study on the average working hours per day, exemplarily for the OWEZ wind farm case study.

In regard to Thanet wind farm, installed as a SP-1T configuration by the MPI Resolution jack-up vessel [15, 18], it emerged that, although pre-assembly configurations could have reduced the installation time by approximately a month, the highest criticality for lifted weight remains with the tower. As the transportation of the tower in a single piece is generally preferred, the tower is indeed usually the heaviest component, and thus presents the greatest lifting hazard. However, due to vessel limitations, transporting the tower in two sections is increasingly required for larger turbines. This may be more cost effective than designing and building specialised “ad hoc" vessels. Subsequently, the following technologies and concepts for transportation and installation are focussed on the tower assembly.

3. Concepts for connections during installation and seafastening during transport

Connections play an important role in offshore wind turbine installation: for the final connection of single lifted pieces, but also for seafastening the turbine components on the transportation vessel. Ring-flange connections are most common for the major components of an offshore wind turbine. Typically, more than 120 high-strength, pre-stressed bolts of large sizes (around M64 or M72 [20]) are used at each flange connection. Mostly, the bolts are already positioned on the wind turbine elements, which saves the labour of manually placing the bolts in the holes. Still, every single bolt needs to be tightened accurately, requiring special equipment such as hydraulic bolt tensioners.

An extensive review has been done on new connection and seafastening methods and designs. Innovative connection solutions include concepts based on friction [21] or the recently developed technology BLUE Wedge [22]. Besides the latter technology, which can also be used for seafastening, hydraulic systems and an internal jack system are proposed as seafastening solutions [23]. Staying with the traditional bolted flange connection, auxiliary systems for accurately tightening the bolts are required to ensure that no failure or hazard occurs due to loose bolts. Automated bolting systems exist [24, 25]; however, in the case of offshore wind turbine installation, the robot has to get on site and up the turbine as well.

The greatest possibility for improvement was found to be in enhanced seafastening methods, particularly regarding tower sections. Hydraulic seafastening would offer both safer and quicker seafastening, and thus increase the weather window compared to the conventional method of manual bolting. In addition, a robot arm employment for automated seafastening bolting is suggested (figure 6), which would retain the reliability of manual bolting while still reducing the risk and increasing the speed. However, the technology and logistical complexity set this study at a preliminary analysis phase.

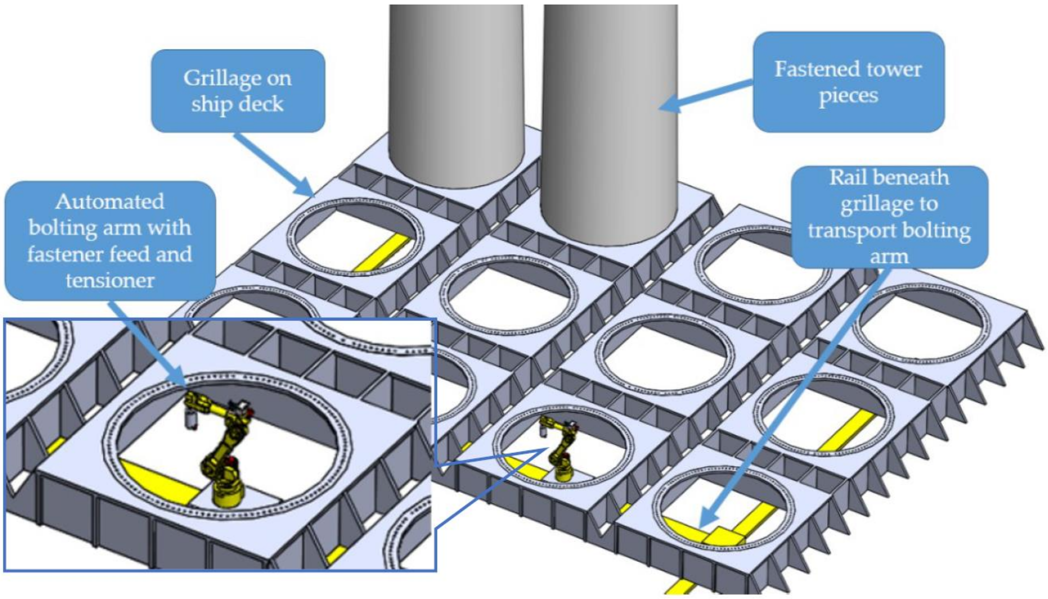


Figure 6. Automated bolted seafastening, concept illustration [14].

4. Concepts for guidance and control auxiliaries for lifting and installation

Guidance and control equipment for global hoisting, the mostly vertical lift from the ground to the aimed level, are already widely employed in lifting operations for wind turbine installations. Large movements during lifting are controlled via taglines. Developed systems, as presented in figure 7, are the Boom Lock [26], the Tagline Master [27], which can be controlled remotely, and the Blade Dragon [28], a remote controlled blade yoke.

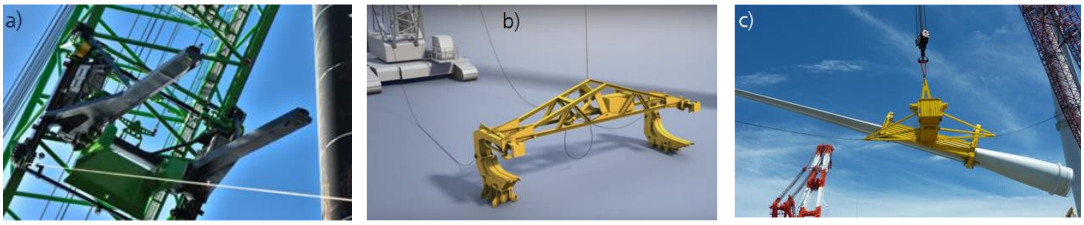


Figure 7. Global hoisting systems: (a) Boom Lock [26], (b) Tagline Master [27], (c) Blade Dragon [28].

When bringing the load close to the counterpart, correct positioning for the final installation has to be ensured. Thus, auxiliaries for centring and rotational alignment are required. Guide pins (figure 8a) or guide rods with corresponding socket sections help to align bolts and bolt holes, whilst cones or funnels (figure 8b) centre the lifted section with respect to the counterpart. The latter method has already been used for a human-free met mast installation [29], but it is quite limited in size. Guide pins on the other hand are commonly used for installation of wind turbine elements; however, as it can clearly be seen in figure 8a, people are still directly involved in the lifting procedure.

To remove personnel from beneath the payload, innovative solutions, such as camera systems together with novel mechanical guidance designs for rotational alignment and centralisation, are required. In this study, simplified small-scale tests were performed to quantify changes in accuracy, operability, and time when banksmen were moved from beneath the payload and visual and/or mechanical guiding elements were employed instead. Thus, three results were of interest: time taken for the lift, centrality, and rotational alignment.

Figure 8. Current use of fine hoisting systems: (a) Guide pins [30], (b) Guiding funnel [29].

The experiments were performed with a cylindrical steel section of 1.314 m outer diameter, 0.022 m wall thickness, and 0.55 m height. This was lifted by means of a standard gantry crane with three axes of movement and a freely rotating boom. Each lift started at the same position, 3.05 m from the target destination - a cylinder cross section drawn on the ground, with markings for bolt locations -, with the same crane operator standing behind a screen and listening for instructions from a banksman. Each test was performed five times and two banksmen alternated instructing the lifts for a more meaningful average result.

Visual guidance was tested for two types of camera - standard cameras (Swann 650TVL CCTV with night vision and 55^{o} field of vision) and a 360-degree camera (Samsung gear-360) - in four different configurations:

(i) three standard cameras equally distributed on the circumference of the lifted cylinder section;
(ii) three standard cameras as in (i) and a fourth attached to the top of the lifting chains;
(iii) one 360-degree camera located in the middle of the target position, as shown in the two videos [31, 32];
(iv) three standard cameras as in (i) combined with the 360-degree camera as in (iii) (figure 9a).

For mechanical guidance, a holistic design was developed, bringing together the technical ideas of existing guiding systems, such as cones for centralisation or guide pins and socket sections for rotational alignment. This mechanical guiding element is removable and reusable as it consists of two parts: a guide rod attached to the lifted part and paired with a socket section within a conical extension attached to the fixed section, as visualized in figure 9b. Three guiding element pairs, equally distributed on the circular flanges, were considered to be sufficient. Adding threads to three sets of two or three bolt holes, the guiding elements can directly be screwed to the top and bottom turbine sections, respectively. After each lift, the elements can be removed again and reused for another lift. The experiments were performed with a simplified model of the mechanical guiding system design, as shown in figure 9c and video [33].

The first experiments focused only on centralisation of the lifted section on top of the (drawn) bottom cylinder with the help of cameras, while the second test campaign focused on centralisation as well as correct rotational positioning, firstly using the best camera setup found from the first set of experiments, then utilizing in addition the mechanical guiding system as shown in figure 9c.

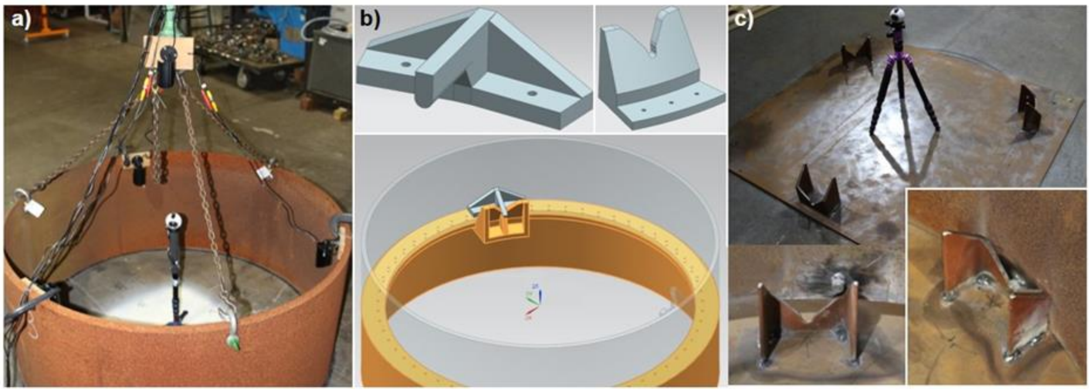


Figure 9. (a) Cameras for visual guidance, (b) Holistic mechanical guiding system, (c) Visual and mechanical guidance experiment setup.

The results are shown in table 1, representing the accuracy with respect to centralisation and rotational alignment, as well as the time taken, including a comparison to manual handling (with banksmen under the load). The first test campaign showed that with the combined setup (case iv) of three circumferential standard cameras and one central 360-degree camera the least eccentricity could be achieved. However, considering the additional criterion of rotational positioning happens at the expense of time and accuracy. Bringing together visual and mechanical guiding systems speeds up the lifting process enormously, while at the same time yielding a perfect fit. The best camera setup (case iv) allows rough and fast positioning of the lifted element above the target position, while the mechanical guiding system automatically positions the two pieces perfectly above each other as soon as the guide rod and bottom guiding element come in to contact (figure 9c).

Table 1. Comparison of the average results for all the configurations tested.

Configuration tested	Time taken [s]	Centralisation error [mm]	Rotation error [deg]
Centralisation only			
Banksmen under load	175.6	4.4	
Case (i): 3 cameras	551.2	15.6	
Case (ii): 4 cameras	496.0	5.2	
Case (iii): 360° camera	349.4	9.0	
Case (iv): 3+360° camera	391.0	4.2	
Centralisation and rotational alignment			
Banksmen under load	225.6	7.8	0.48
Case (iv) (3+360° camera)	498.4	4.9	1.36
Case (iv) + mech. guidance	202.0	0.0	0.00

Although, one has to keep in mind the time for connecting and removing the guiding element, the manually guided lift would take much longer than stated in the experiment, as it would have to be performed as slow enough to eliminate any eccentricity and rotational misalignment with the help of guiding hands. Therefore, the use of cameras in combination with the developed mechanical guiding elements could speed up an offshore lifting process by a factor of two, based on not too optimistic estimations, without posing risk to any person.

The wind turbine installation time can be related to the corresponding costs, which make up around 2% of the total offshore wind farm installation cost, based on information from Offshore Design Engineering Limited [34] for an offshore wind farm with around $1.6M/MW installed. Assuming that performing the lifts makes up just 20% of the total time for the wind turbine installation due to the long travelling distances, it can be estimated that lifting operations account for 0.4% of the capital expenditure for an offshore wind farm. Depending on conditions and size of a specific wind farm, it can be expected that the fabrication costs of the reusable mechanical guiding elements, as well as the acquisition costs for the cameras will at least pay for itself and may even enhance economic gains during the installation of one offshore wind farm.

5. Conclusion

The present work provides feasible solutions for human-free offshore lifting operations. Guidance and control systems, automated bolting or hydraulic seafastening, as well as a tool for optimised planning of offshore wind turbine logistics and installation, can help to remove people from beneath loads and thus contribute to increased safety in offshore lifting operations. In particular:

- The developed program for installation logistics outlines advantages and possible sensitivities of different installation procedures.
- A novel, although preliminary, concept for seafastening has been suggested.
- Supplementing existing tools, such as Boom Lock and taglines, by a holistic solution for visual and mechanical guidance, consisting of three circumferential cameras and one 360-degree camera, as well as innovative reusable guiding elements, can lead to faster and highly accurate offshore lifting procedures without putting personnel in dangerous areas. This will not only speed up the lifting operation itself but is also expected to entail financial benefit in offshore wind farm installation.

Regardless of the additional economic benefit, cameras and mechanical guiding elements are easy to implement and would crucially reduce the number of incidents during installation work by removing people from the high-risk areas. Increased safety and protection of life should be of highest priority.

Acknowledgments

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Geddes, and Joe O'Toole from Ørsted for their insights into the industries' current practices and needs.

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Annex D

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Human-Free Offshore Lifting Solutions

Cranfield University
University of Oxford
REMS CDT
DONG
G+

Group Project
Academic Year: 2016 – 2017

Supervisor: Prof. Feargal Brennan
April 2017

1 Introduction

It has been estimated that installed capacity of offshore wind energy could expand from the present 12.6 GW to 24.6 GW by 2020 (EWEA, 2016). As such, the number of lifting operations performed each year could also grow in parallel.

Data for health and safety incidents reported annually, occurring during offshore lifts, were provided by G+ (G9 Offshore Wind Health & Safety Association, 2014, 2015). From this, the total number of incidents and dropped objects per hour of work was determined (Figure 1). Although relatively small, an increase in incidents and dropped objects in 2016 indicates that safety during lifts had not improved. There was one incident in 2014 and two in 2015 which required medical attention. A restricted work day occurred in 2014, 2015 and 2016; a lost work day occurred in 2014 and 2015. There were 11, 22 and 26 incidents in 2014, 2015 and 2016 respectively that were identified as having a high potential for severe consequences (serious injury, mortality or structural damage).

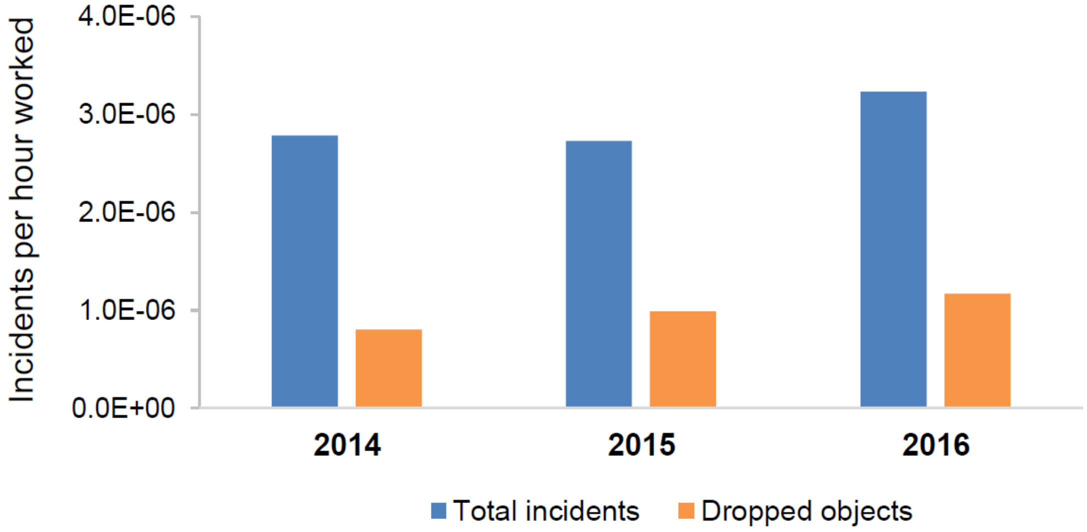


Figure 1: Total incidents and dropped objects per number of hours worked

The motivation for this project was to conduct research into methods and technologies that could reduce the need for personnel near lifting operations, and to assess their feasibility. Whilst there will always be a degree of risk in offshore lifting operations, removing personnel away from suspended loads would considerably improve human safety.

This consolidated report summarises our findings for solutions for lifting operations during the construction of offshore wind turbines. The selection of the most promising solutions was determined via a multi-criteria decision analysis (MCDA). The methodology and results of the MCDA are outlined in chapter two. The full report (Balaam et al., 2017) details several concepts for the identified macro-areas of research for ‘Guidance and Control’, ‘Connections and Seafastening’, and ‘Assembly Solutions for Installation’. However, here we present only the solutions that were determined to be the most promising and closest to implementation.

2 Methodology

2.1 Criteria Ranking: Survey and MCDA

Numerous ideas and novel human-free lifting concepts have been presented in the full report, all of which aim to reduce the risk to personnel. The selection of the optimum solutions, however, cannot simply be based on a single criterion. This presented a multi-dimensional problem leading itself to a MCDA. The purpose of the MCDA, was to analyse each idea and then combine them through a logical process to present an overall picture, ranking the viability of equipment and processes to reduce the need for people beneath loads during the construction stage lifting operations of offshore wind turbines at sea.

21 criteria were determined through two brainstorming sessions within the group, involving research and development, operational and manufacturing aspects. Subsequently, an anonymous survey was distributed through G+ and other company contacts via a link to an online portal ‘surveymonkey.com’. Thanks to 40 respondents (38 industrial and two from academia), the criteria have been ranked and weighted, accounting for the years of experience and expertise of the participants.

2.2 Criteria Satisfaction and Ideas Selection

One of the most challenging parts of this MCDA was the determination of how well each alternative satisfies the criteria. Due to the immature nature of the concepts and technologies investigated in this study, the criteria satisfaction was based on personal judgement of the researchers. In particular a two-stage TOPSIS method was applied (Figure 2). Initially, the analysis served as a guide to the research team to refine the brainstormed concepts within the main groups of concepts for human-free lifting operations identified. In the final stage, the members of the group gave criteria satisfaction values to all of the technologies presented to provide a recommendation to industry for future development.

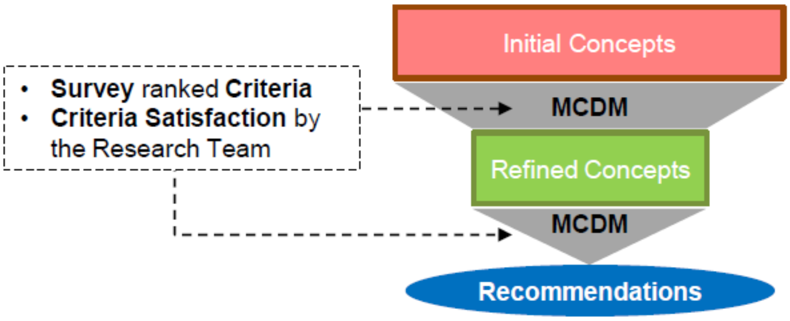


Figure 2: Methodology workflow

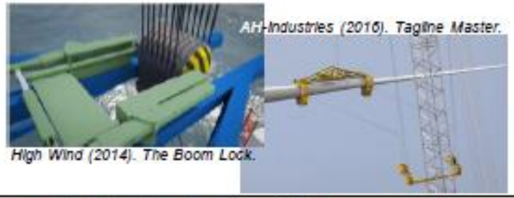
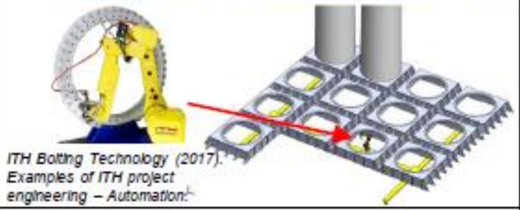
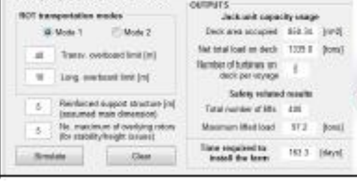
The final logical ordering of the most promising options, based on the above described ranking methods, are reported in Table 1. Despite the inherent limitations, this method of evaluation was deemed sufficient in light of the objective of the MCDA implemented and for the early nature of this report. More information and extensive explanation on the methodology adopted for this study are covered in (Balaam et al., 2017) in Chapter 4.

3 Development of Solutions

3.1 Refined Concepts Overview

The technologies and processes reported in Table 1 were shown to be the most promising novel concepts by the MCDA to potentially reduce the occurrence of lifting related incidents in the offshore wind turbine transportation and installation industry.

Table 1: Refined concept ranking and schematics

Technology/ Process	TOPSIS Coeff.	Concepts Schematic	Contribution Level
Boom Lock and taglines	0.6719	 AH-Industries (2016). Tagline Master. High Wind (2014). The Boom Lock.	Employability from onshore operations
Camera system and mechanical guidance	0.6166	 Guiding experiments setup	Preliminary feasibility (experiment) and design
Robot arm for Seafastening	0.6137	 ITH Bolting Technology (2017). Examples of ITH project engineering – Automation.	Employability of new technology
Boom Lock, taglines, mech. guidance and cameras	0.5952	*(see above)*	Employability
Current pre-assembly practise optimisation	0.5949	 	Software development

In regard to onshore pre-assembly and offshore transportation practise, the team worked on the development of a lifting operation optimisation program, with the aim to forecast the advantages and limitations of procedures currently in use. Although the software has been validated against actual case studies (Thanet and OWEZ wind farms installation), showing a good agreement with real time taken to install, case-specific variables (wind turbine dimension, vessels characteristics and availability, as well as weather window conditions and duration) made the suggestion of the best method to implement difficult.

For bolting and seafastening solutions, an extensive review has been done on new connection methods and designs. Automated technologies available for securing the payload on vessels and installing equipment on site were considered. In particular a robot arm employment for seafastening bolting has been suggested, rather than the more costly hydraulic solution, offering the possibility to shorten the loading and unloading operation time and potentially increasing the weather window. However, the technology and logistical complexity set this study at a preliminary analysis phase.

On the other hand, control and guidance devices, classified and developed in the concepts of global and fine hoisting, were developed further, thanks to their ease of availability and setup. Equipment such as Boom Lock and taglines, already widely employed in onshore lifting operations to improve accuracy and control of global hoisting, showed the highest score in the TOPSIS analysis. Furthermore, the use of camera systems together with novel mechanical guidance designs for rotational alignment and centralisation improvement, ranked immediately after, mainly due to their innovative nature. Despite the availability of the former, these technologies would still require humans beneath the lift to guide design. Thus, a more in-depth analysis and feasibility study were conducted for the visual and mechanical guiding devices, to better define the benefits achievable by their use in offshore lifting operations.

3.2 Camera System and Mechanical Guidance In-view

Of the concepts presented in this study, the use of cameras and mechanical guiding elements were one of the most promising, based on the MCDA (Table 1). Thus, this section focuses on the development of this solution in more detail.

Visual and mechanical guidance, separately and combined, were examined in simplified small-scale tests, designed to mimic an offshore lift of a cylindrical tower section. The experiments did not aim to recreate conditions offshore but rather attempted to quantify changes in accuracy, operability, and time when banksman are moved from beneath the load to a safe location and cameras and/or mechanical guiding elements are employed instead. The target unloading position was drawn on the ground with the cylinder cross section and markings for bolt locations. A standard gantry crane with three axes of movement (x, y, and z) and a freely rotating boom was used for lifting a cylindrical steel section of 1.314m outer diameter, 0.022m wall thickness, and 0.55m height. The same boundary conditions were used throughout the laboratory tests: each lift started at the same position, 3.05m from the target destination, with the same crane operator standing behind a screen and listening for instructions from a banksman. For reasons of safety and a more realistic representation of the test results, two banksmen were involved, one giving the instructions to the crane operator based on the camera views on a monitor, and the other staying close to the load for safety and to reduce large motions and thus imitating remote taglines. Each test was performed five times and the banksmen switched their roles half way through for a more meaningful average result.

The experiments focused on three results: 1) time taken for the lift, 2) eccentricity measured as the distance from the unloaded cylinder centre to the targeted centre, and 3) rotational misalignment, measured as the angle between the bolt positions of the unloaded section and the bottom cylinder.

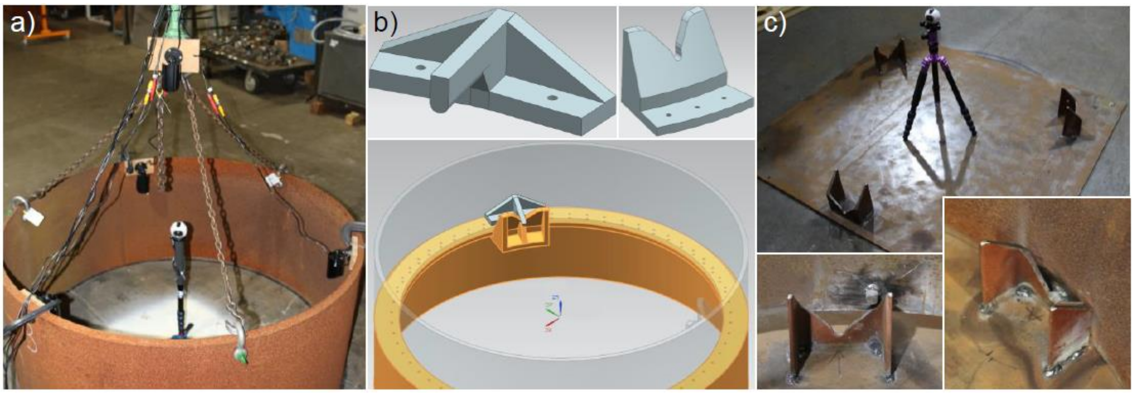


Figure 3: a) Cameras for visual guidance, b) Holistic mechanical guiding system, c) Visual and mechanical guidance experiment setup

The first experiments focused only on centralisation of the lifted section on top of the bottom cylinder with the help of cameras. As a reference, mimicking the current practice offshore, a test with banksmen being under the load and manually guiding the load was performed. Whilst quite fast, this was not very accurate as each banksman just had a finite view and therefore could not see the position of the load as a whole. Camera guidance, where the banksmen were removed from beneath the load, was tested with four different camera configurations (Figure 3-a), using standard cameras (Swann 650TVL CCTV with night vision and 55° field of vision), as well as a 360-degree camera (Samsung gear-360): 1) three standard cameras equally distributed on the circumference of the lifted cylinder section, 2) three standard cameras as in case 1 and a fourth standard camera attached to the top of the lifting chains approximately 2m above the base of the cylinder in taught-chain condition, 3) one 360-degree camera located in the middle of the target position raised approximately 0.05m above the ground, as shown for one test in the videos (Balaam and Leimeister, 2017a, 2017b), and 4) three standard cameras as in case 1 combined with the 360-degree camera as in case 3. The use of cameras took more than twice as long as the manually guided test; however, less eccentricity could be achieved with setup 4, which used three circumferential standard cameras and one central 360- degree camera. The results are presented in Figure 4, shaded as rotational alignment is not included.

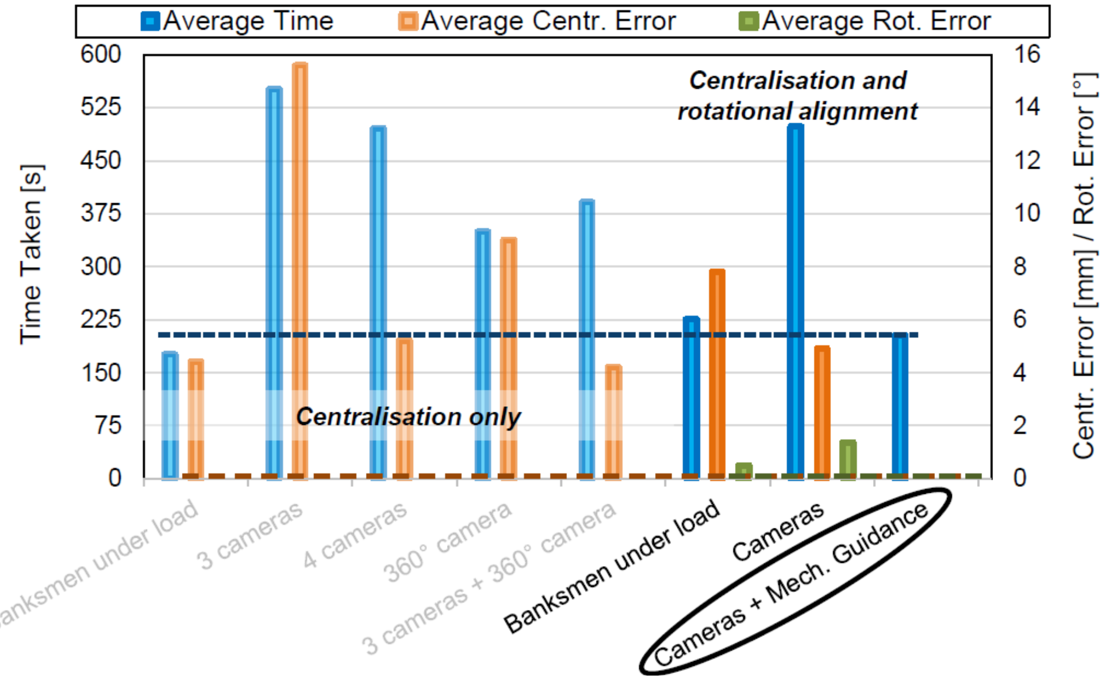


Figure 4: Comparison of the average results for all the configurations tested (the dashed lines continue the results of the best solution with cameras and mechanical guidance)

Further tests focused on centralisation as well as correct rotational positioning. Considering this additional criterion happens at the expense of time and accuracy in both the cases of manual handling and utilizing the best camera setup, as shown in Figure 3-b. For this reason, mechanical guidance was added. Bringing together the technical ideas of existing guiding systems, such as cones for centralisation or guide pins and socket sections for rotational alignment, a holistic mechanical guiding element was designed, consisting of a top part with a guide rod and a bottom part with a corresponding socket section within a conical extension, as visualized in Figure 3-b. Three of these guiding element pairs are expected to be sufficient, if positioned equally distributed on the circular flanges. Adding threads to three times two or three bolt holes, the guiding elements can directly be screwed to the top and bottom turbine sections, respectively. After each lift, the elements can be removed again and reused for another lift. Experiments were performed with a simplified model of that mechanical guiding system design, shown in Figure 3-c and video (Balaam and Leimeister, 2017c). The best camera setup, found from the previous tests, allowed rough and fast positioning of the lifted element above the target position, while the mechanical guiding system automatically positioned the two pieces perfectly above each other as soon as the guide rod and bottom guiding element come in to contact (Figure 3-c). The results (Figure 4) represent the exact positioning and, moreover, the saved time compared to manual handling.

Although, one has to keep in mind the time for connecting and removing the guiding element, the manually guided lift would take much longer than stated in the experiment, as it would have to be repeated until eccentricity and rotational misalignment are eliminated. Therefore, the use of cameras in combination with the developed mechanical guiding elements could speed up an offshore lifting process by a factor of two, based on not too optimistic estimations.

The wind turbine installation time can be related to the corresponding costs, which make up around 2% of the total offshore wind farm installation cost, based on information from Offshore Design Engineering Limited (Offshore Design Engineering (ODE) Limited, 2007) for an offshore wind farm with ~£1.6M/MW installed. Assuming that performing the lifts makes up just 20% of the total time for the wind turbine installation due to the long travelling distances, it can be estimated that lifting operations account for 0.4% of the capital expenditure for an offshore wind farm. Depending on conditions and size of a specific wind farm, it can be expected that the fabrication costs of the reusable mechanical guiding elements, as well as the acquisition costs for the cameras will at least pay for itself and may even enhance economic gains during the installation of one offshore wind farm.

4 Conclusion and Recommendation

To summarise, guidance and control systems, automated bolting or hydraulic sea-fastening, as well as novel concepts and a tool for optimised planning of offshore wind turbine work can help to remove people from beneath loads and thus contribute to increased safety in offshore lifting operations. In particular, a holistic solution for visual and mechanical guidance, using three circumferential cameras and one 360-degree camera, as well as innovative reusable guiding elements, combined with the use of existing tools such as Boom Lock and taglines, would allow for faster and highly accurate performance of offshore lifts without putting personnel in dangerous areas.

To gain a substantially more exact statement on the final design of the guiding elements and the time and cost savings, a more detailed cost analysis is required, and a full-scale design has to be developed and tested. For the latter it has to be ensured that both guiding elements remain structurally intact during the lifting and guiding process, but are, at the same time, light enough to be manually handled by one banksman for connection to and removal from the flange. Alternative materials, such as glass fibre reinforced polyester, could be considered.

Regardless the amount of additional economic benefit, the use of cameras and mechanical guiding elements in offshore lifting operations will definitely reduce the number of incidents during installation work. Increased safety and saved lives should be of highest priority.

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