THE BIODIVERSITY, ECOSYSTEM FUNCTIONING AND VALUE OF RESTORED SALT MARSHES IN THE EDEN ESTUARY, SCOTLAND

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

2018

The biodiversity, ecosystem functioning and value of restored salt marshes in the Eden Estuary, Scotland

Katherine Scarlett Wade

This thesis is submitted in partial fulfilment for the degree of

Doctor of Philosophy (PhD)

at the University of St Andrews

July 2018

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Acknowledgements

Where to begin! It has been a long journey to get to this point and there are so many people who have helped me along the way.

Firstly, thank you to my supervisors, Prof David Paterson, Prof Nick Hanley and Dr Claire Gollety, thank you for your support and advice through the ups and downs! This project was a steep learning curve with me having little knowledge of ecosystem services and even less knowledge of valuation methods at the start! Thanks to Nick for answering my questions, no matter how daft they were and for your guidance, particularly in the early stages. To Claire, thank you for your support and for your meticulous planning and attention to detail – you always pushed me to challenge myself. To Dave, thank you for your advice and guidance and for sticking with me at the end!

To the SERG team, thank you for the endless entertainment during coffee breaks and general support. To those who helped me in the field I owe massive thanks, especially Irv and Jack. Without you this thesis would not have been possible and field work would have been far less fun! To Pam and Joe, thank you for making the long hours looking down a microscope amusing, the continuous banter and music kept me sane! Thank you also to all the student volunteers who helped with this task.

Big thanks must also go to Dr Clare Maynard. Without your work, my work would not have been possible! Your wealth of knowledge about the estuary and huge network of contacts is truly impressive. Thank you for always lending an ear when needed, through the good and the bad!

Thanks must also go to Dr Dugald Tinch for your advice in designing the choice experiment, and to Dr Laure Kuhfuss for assistance in the analysis. Thanks also to all the people who assisted in the development of the survey, whether it was through an interview, focus group or just completing the survey!

Thank you also to MASTS and the University of St Andrews for the funding that made it possible to undertake this project.

Last but by no means least, a massive thanks to my family and friends. Without your continuous support, encouragement and faith, I would not have got to this point.

Contents

Abstract

The ecosystem service (ES) framework is increasingly being incorporated into management decisions, providing a basis by which ES can be quantified to understand the impact of decisions to society and the environment. Our ability to effectively implement this framework is dependent on our knowledge of the links between natural capital, ecosystem functions and ES. A need to ensure that the theoretical model is grounded in scientific evidence exists. This thesis employed ecological and economic methods to apply the ES framework in assessing the ability of restored salt marsh to provide coastal defences, and the perceived value of this by the public.

Using sites planted as part of ongoing restoration in the Eden Estuary, Scotland, ecosystem functions important to the provision of coastal flood defence were assessed for equivalence to natural salt marsh sites. Plant structure was found to develop along a trajectory expected to attain comparable ecosystem function to a natural marsh. Comparable plant height was attained 10 years after planting, however marginal significant differences were still present in plant density. Due to high spatial and temporal variation no trajectory for sediment stability could be inferred. Overall, this work suggests that equivalent coastal defence provision is highly likely to be attained within the planted sites. Comparable benthic macrofaunal species richness and abundance were observed 2-3 and 4–9 years after planting, respectively; community assemblage continued to differ after 11 years. A choice experiment indicated a clear dislike for the use of engineered walls and a preference for nature-based defences within the Eden Estuary. A combination of a low wall and fronting salt marsh was preferred with the highest willingness to pay.

Combining the findings from ecological and economic research enables insights that can assist in the planning of coastal flood defence providing valuable information to managers and policy makers.

Chapter 1: General Introduction

1.1. Introduction

Society depends on the natural environment for a wide variety of benefits which are critical for human well-being. Awareness of the importance of the natural environment has long been recognised, alongside our negative influence, which has led to the loss and deterioration of many ecosystems worldwide. The United Nations (UN), through the Convention on Biological Diversity (CBD), Millennium Development Goals (MDG) and Sustainable Development Goals (SDG), have placed the concept of sustainable management and protection of biodiversity at the forefront of global environmental policy and management (United Nations, 1992, 2015a, 2015b; Secretariat of the Convention on Biological Diversity, 2005). Sustainable management of the environment has been defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987).

The Ecosystem Approach (EA), officially adopted at the CBD in 2004, employs an integrated approach, combining management and policy, to achieve goals aimed at promoting conservation and the sustainable use of the environment by placing biodiversity at the centre of human society (Secretariat of the Convention on Biological Diversity, 2004; Haines-Young and Potschin, 2009). The holistic EA considers environmental, economic and social factors, known as the three pillars of sustainability, across a landscape scale (Secretariat of the Convention on Biological Diversity, 2005). The development of this approach initiated the switch from management which focussed on conserving the nature for its intrinsic value (‘because we should’), to one where we manage nature because of the benefits it provides to society (Mace, 2014). The necessity for this utilitarian process-driven approach has led to the development of the ecosystem services (ES) framework and natural capital (NC) accounting (TEEB, 2010; UKNEA, 2014; Liquete *et al.*, 2016). These concepts create an argument at a policy and management level for conserving the natural environment in terms of the benefits it provides to human well-being. The development of valuation methods capable of placing monetary values on NC and ES, in combination with the ES framework, has enabled decision makers to consider the impacts of activities or developments within the existing economic framework using traditional tools, such as cost-benefit analysis (Farber, Costanza and Wilson, 2002; Newcome *et al.*, 2005; Defra, 2007; UKNEA, 2014; Ozdemiroglu and Hails, 2016; CICES, 2017).

1.2. Natural Capital and the Ecosystem Services Framework

NC and the ES framework provide a conceptual model by which the benefits that the natural environment provides us are incorporated into the current economic framework used globally. Traditionally decisions have been made based on societal or financial criteria where future scenarios are assessed and the option with the greatest human well-being, or greatest capital gains, are chosen (Daily, 1997; Costanza *et al.*, 2014; Liquete *et al.*, 2016). Capital has been categorised in many ways (Table 1.1) and the typology may vary. However, in all cases capital is a term used to define a stock of something whether it be money, goods, infrastructure or knowledge (Palomo *et al.*, 2016). The traditional way that decisions have been made, with limited consideration to NC, has enabled the growth of other types of capital at the expense and exploitation of the environment, resulting in the degradation of ecosystems (Millennium Ecosystem Assessment, 2005c). Incorporating the natural environment or NC, alongside human, social, manufactured and financial capital, into decision making, through the application of the ES framework, promotes the more sustainable use of the environment (Figure 1.1).

Table 1.1: Definitions for types of capital assets. (Adapted from Box 1, Polomo et al, 2016)

Type of Capital	Definition
Human Capital	People's health, knowledge, education, skills and motivations. Incorporates intellectual capital.
Social Capital	Assets associated with formal and informal networks, trust, shared values and norms required for enhancing the quality and quantity of societal interactions. It facilitates coordination and cooperation for mutual benefit.
Manufactured Capital	Fixed physical assets which contribute to the production process of good and services e.g. tools, machines, infrastructures, buildings and other built capital.
Financial Capital	Virtual mechanism that society uses to trade other forms of capital. It includes savings, credits and money used for investing in the maintenance and enhancement of other capital assets.
Natural Capital	The stock of natural resources that provide goods and services to society. It is necessary to maintain life on Earth and human well-being.

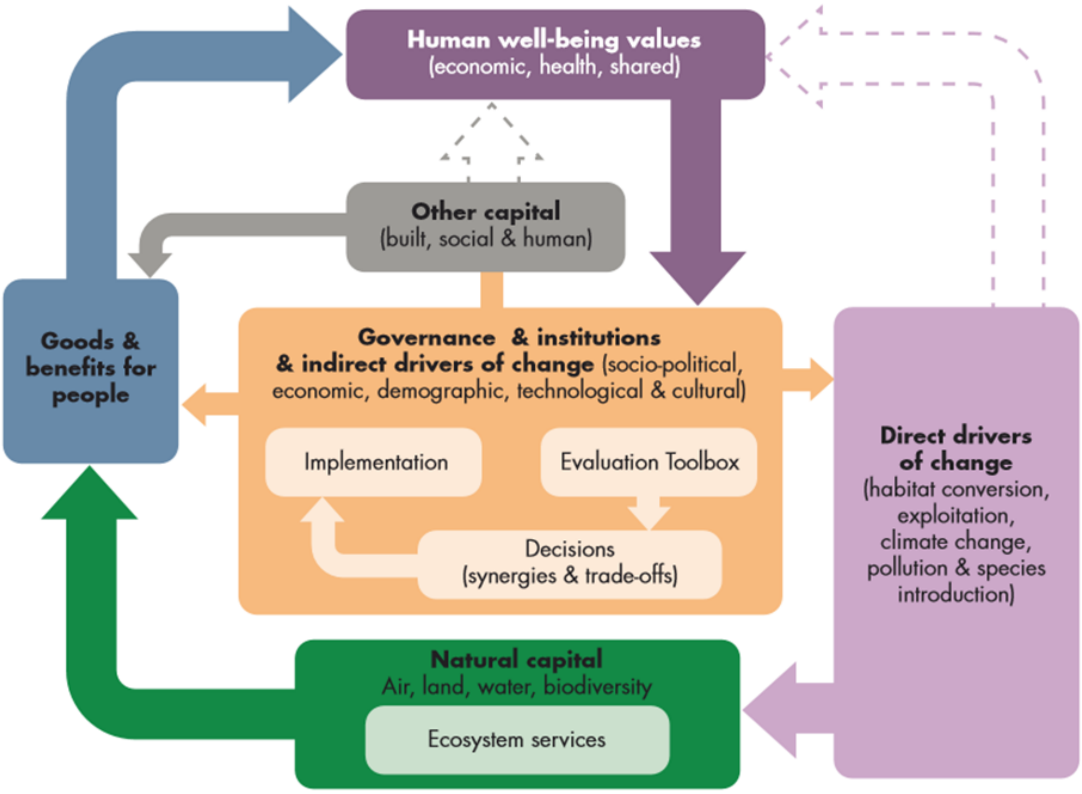


Figure 1.1: The Ecosystem Services Conceptual Framework illustrating how natural capital and ecosystem services fit within the wider context of human, built and social capital, and the role of governance and institutions in the decision-making process (From UKNEA, 2014).

NC is defined as "the configuration (in time, space, functionality and/or with other capital) of natural resources and ecological processes that contributes through its existence and/or in some combination to human welfare" (UKNEA, 2014). More simply it can be defined as the stocks of renewable, and non-renewable resources, which include all natural biotic and abiotic components. NC or its components, underpin the provision of all other types of capital; interactions with which contribute to human well-being, with built and human capital, the constituent parts of the economy, being embedded within society (Figure 1.2) (Cardinale *et al.*, 2012; Costanza *et al.*, 2014; Harrison *et al.*, 2014; Liquete *et al.*, 2016). To incorporate NC into the economic driven framework used by society it is necessary to understand the links between, and ascribe values to, the natural stocks and the benefits that humans obtain from them; the ES framework provides this vital link.

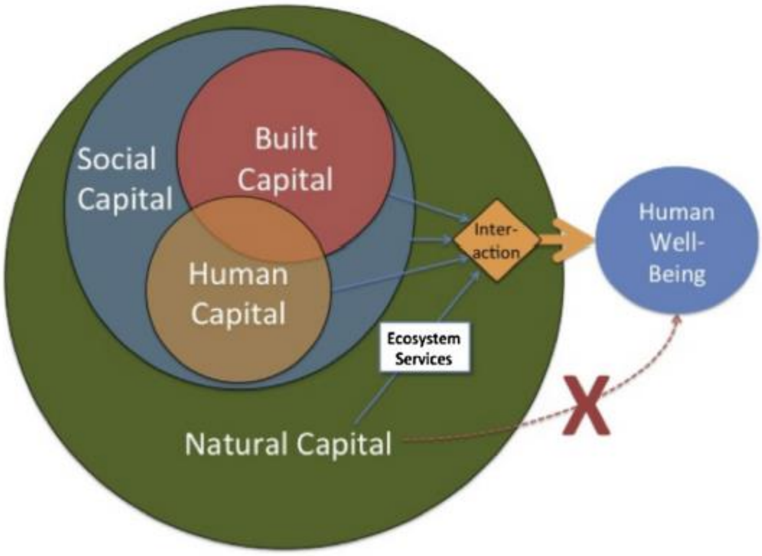


Figure 1.2: Relationship between types of capital and human well-being (From Costanza et al., 2014).

The concept of the ES framework became commonplace following the Millennium Ecosystem Assessment (MA), an interdisciplinary and international project commissioned by the UN (Millennium Ecosystem Assessment, 2005a; Haines-Young and Potschin, 2009; De Groot, Braat and Costanza, 2017). Through this project, which was the first global assessment of ES across all major ecosystems to take place, the first conceptual model of the ES Framework was produced (Haines-Young and Potschin, 2009; De Groot, Braat and Costanza, 2017). Interdisciplinary projects and networks operating at local to global scales have continued to develop this conceptual model, with an increasing number of case studies applying the framework in the ‘real world’, providing valuable developments in the practical uses and application of the framework (for example table 1.2).

Table 1.2: Examples of key projects or networks involved in the development of the Ecosystem Service Framework and associated research.

Project Name	**Year**	**Website**
Millennium Ecosystem Assessment (MA)	2001 – 2005	http://www.maweb.org/
The Economics of Ecosystems and Biodiversity (TEEB)	2007	http://www.teebweb.org/
United Kingdom National Ecosystem Assessment (UK NEA)	2008 - 2011	http://uknea.unep-wcmc.org/
The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)	2012 -	https://www.ipbes.net/
United Kingdom National Ecosystem Assessment Follow On (UK NEAFO)	2012 - 2014	http://uknea.unep-wcmc.org/
VALMER	2012 – 2015	http://www.valmer.eu/
Valuing Nature Network	2014 - 2019	http://valuing-nature.net/
Natural Capital Initiative	2009 -	http://www.naturalcapitalinitiative.org.uk/
NERC Biodiversity & Ecosystem Service Sustainability	2011 - 2017	http://www.nerc-bess.net/
Common International Classification of Ecosystem Services (CICES)		https://cices.eu/

As expected in an area with extensive ongoing research, the conceptual model is continuing to evolve together with the research. The potential for misunderstandings in evolving research such as the ES framework, has raised concerns, particularly with multiple disciplines and projects trialling the concept globally. The importance of defining clearly the terms within developing research and the consequences of failing to do this have been detailed (Wallace, 2007; Paterson, Defew and Jabour, 2012; Díaz *et al.*, 2015; CICES, 2017). In response, working groups have been created to develop a common classification for relevant terminology across sectors and disciplines. CICES, a European Environment Agency group, published their first classification in 2013, and contribute to the global UN platform of SEEA, creating a standard classification and terminology (CICES, 2017).

1.2.1. Ecosystem Services Classification

ES are the “benefits provided by ecosystems that contribute to making human life both possible and worth living” (UKNEA, 2014) and include direct tangible benefits, such as food and water, and indirect, often intangible benefits such as natural hazard protection and climate regulation. The ES framework simplifies the complexity of the environment into a list of benefits, or ES (Figure 1.3) (Millennium Ecosystem Assessment, 2005a) which can be measured in terms of losses and gains. Subsequently, the impacts of a policy decision, or a development, on NC can be more easily understood by non-scientists and policy makers (Beaumont *et al.*, 2007; Díaz *et al.*, 2015; De Groot, Braat and Costanza, 2017). The concepts of ES and NC are integral to one another. The ‘flow’ of ES depends on NC, and the provision of ES impacts the quality and quantity of NC ‘stock’ available. Over-exploitation of ES may degrade NC and is not sustainable long term. Equally, the restoration or creation of NC may enhance the provision of ES.

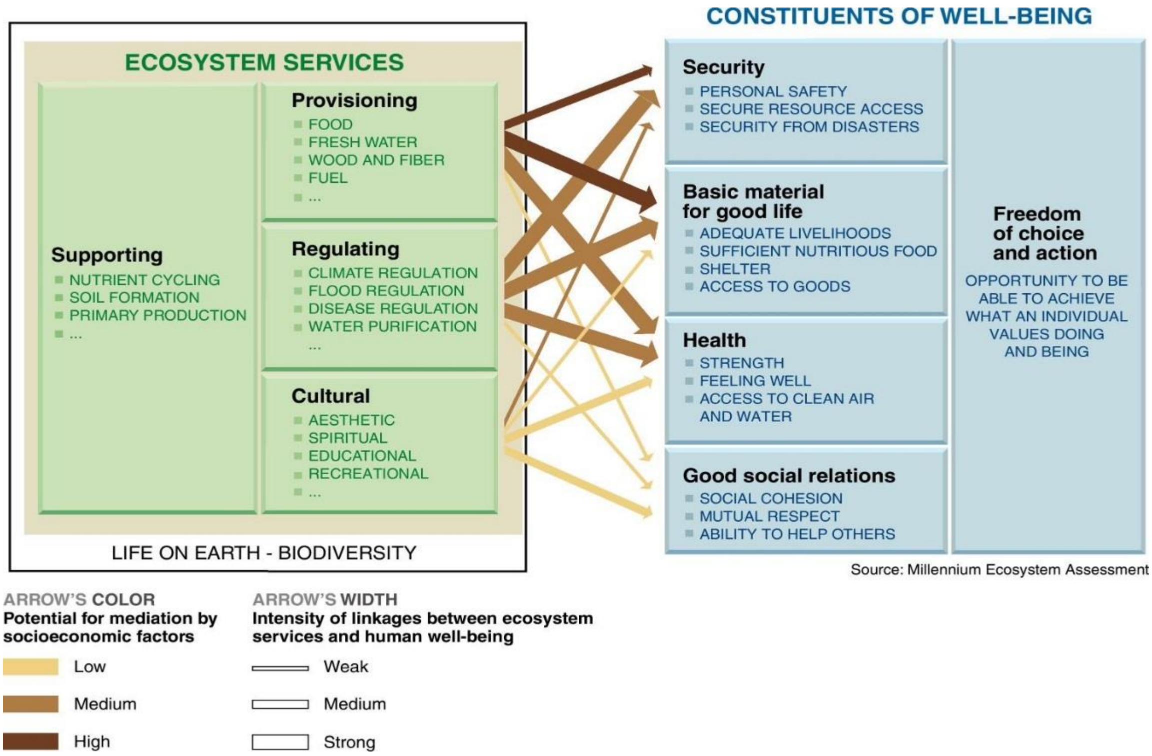


Figure 1.3: The links between ecosystem services and human well-being (from Millennium Ecosystem Assessment, 2005)

ES are commonly divided into four groups (Figure 1.4): provisioning, regulatory, cultural and supporting services, which through interactions with other types of capital (Figure 1.2) deliver goods and benefits which impact human-well-being (Costanza *et al.*, 2014; UKNEA, 2014). Provisioning services are the products that are obtained directly from ecosystems such as food, fresh water and genetic resources. Regulating services are the benefits obtained through the regulation of ecosystem processes such as climate regulation, hazard regulation, which includes coastal and flood defence, and regulation of water, air and soil quality. Cultural services are the non-material benefits that people obtain including spiritual and religious enrichment, recreation and tourism and cultural heritage. Finally, supporting services are the processes that are necessary to maintain all other ES and as such are indirectly beneficial, for example nutrient and water cycling, primary production and soil formation. Supporting services are considered to be intermediate services, and provisioning and cultural services are considered final services; regulatory services can belong to either category (Figure 1.4).

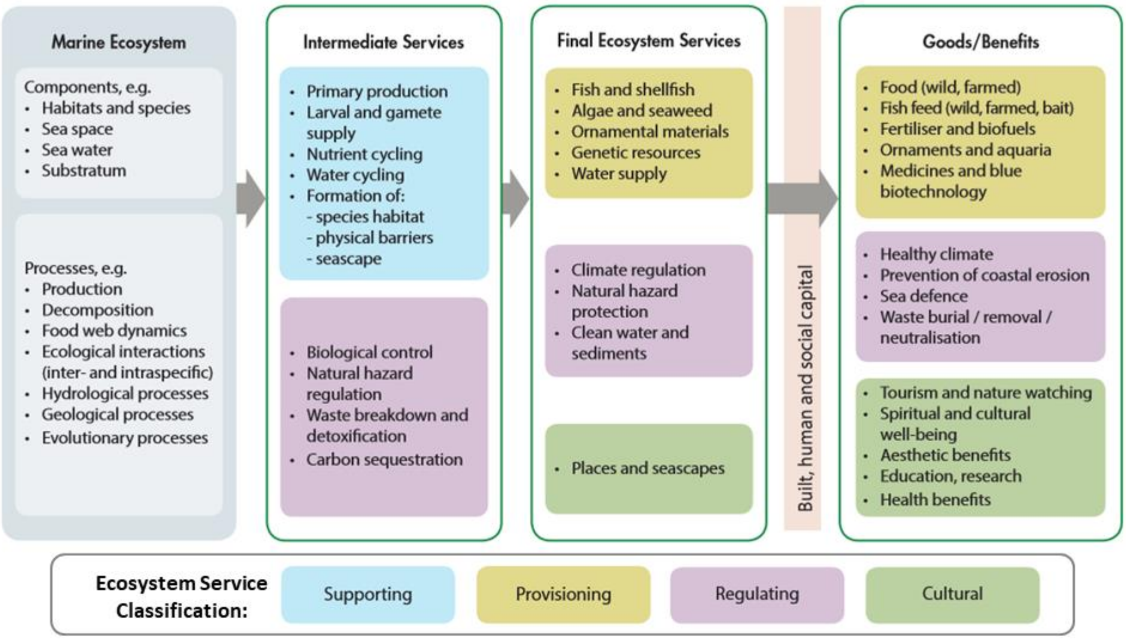


Figure 1.4: The classification of ecosystem services, and goods and benefits for coastal and marine ecosystems. Adapted from the conceptual framework of the UKNEA (UKNEA, 2014).

1.2.2. Biodiversity and Ecosystem Functioning

Whilst using the ES framework to break down and describe the complexity of NC in terms which can be readily understood by non-scientists, it is important not to overlook the importance of our understanding of the relationships that underpin ES. ES are ultimately dependent of the organisms within an ecosystem (biodiversity) (Figure 1.5), however it is the ecosystem functions performed by these organisms that generate ES (Beaumont *et al.*, 2008; Haines-Young and Potschin, 2009; TEEB, 2010). Ecosystem functions (EF) can include the structures and processes produced or undertaken by the compliment of living organisms (biodiversity) and their interactions with abiotic and biotic components of an ecosystem (Haines-Young and Potschin, 2009). One or more processes contribute towards an EF, and one or more EF which offer a benefit to humans contribute to an ES. Processes and EF may contribute to more than one ES and they are all influenced by biological, chemical and physical factors (Paterson, Defew and Jabour, 2012). It is important to note that the capacity of an ecosystem to perform an EF does not always equate to the provision of an ES. ES are only derived from EF that humans perceive as beneficial (Haines-Young and Potschin, 2009).

Changes in the delivery of ES are ultimately due to changes in the biodiversity and their EF provision ability. A clear and positive link between biodiversity and EF has been demonstrated in many experimental and meta-analysis studies (Loreau *et al.*, 2001; Hooper, Chapin III and Ewel, 2005; Balvanera *et al.*, 2006; Worm *et al.*, 2006; Cardinale *et al.*, 2012; Harrison *et al.*, 2014). By monitoring the biodiversity and EF of a system we can assess the ability of an ecosystem to deliver ES. Additionally, understanding the processes behind the provision of EF and how these are influenced by anthropogenic or natural changes will enable modelling of the change on ES delivery and subsequently their value (TEEB, 2010; Balvanera *et al.*, 2014; UKNEA, 2014).

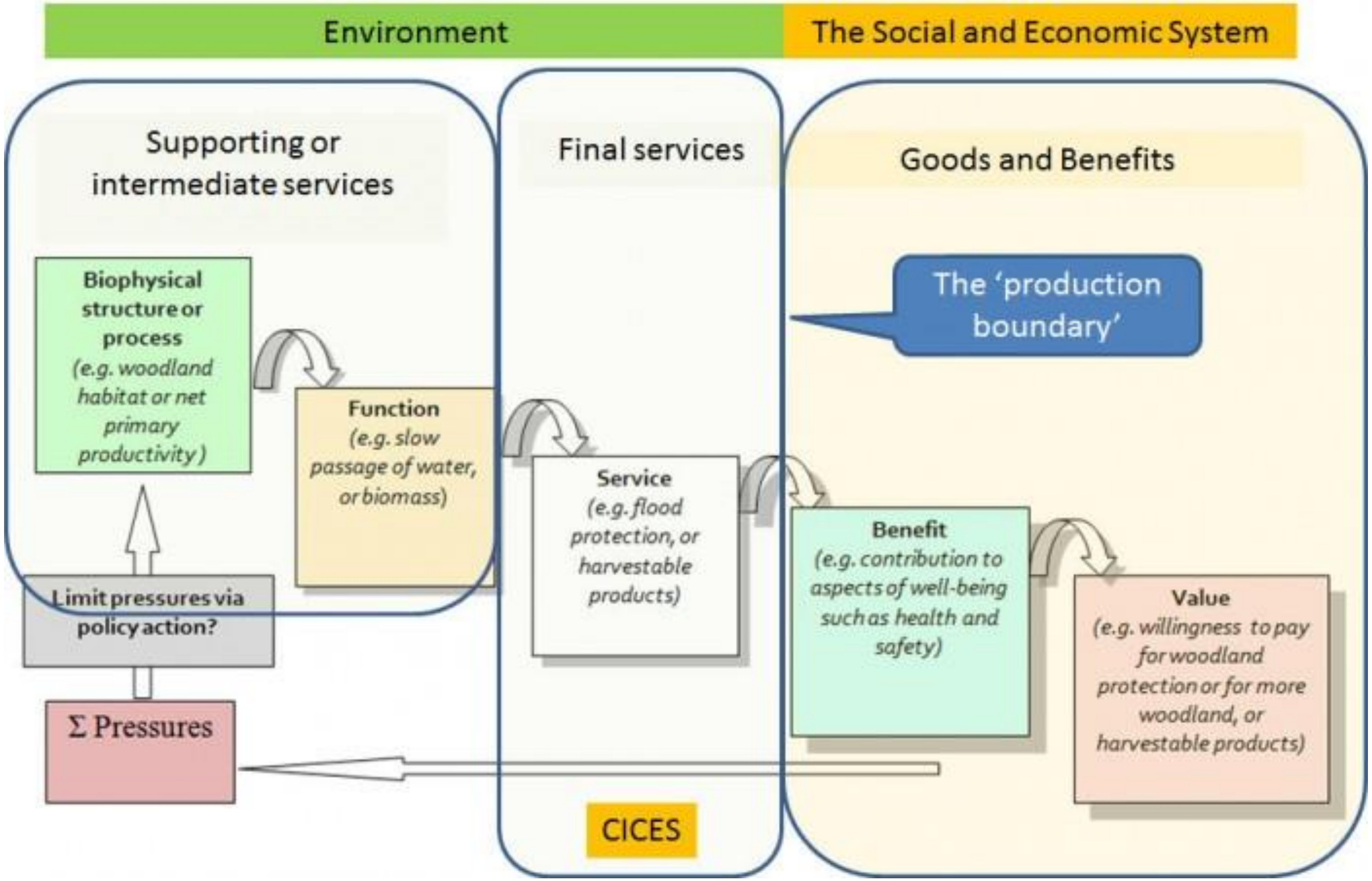


Figure 1.5: The relationship between biodiversity, ecosystem function and human well-being. (From CICES, 2017; adapted from Haines-Young & Potschin 2010).

1.3. Ecosystem Valuation

The aim of the ES framework is to provide a process by which we can more sustainably manage the natural environment. Whilst simplifying the benefits the natural environment provides to society into a list of ES makes it more understandable to non-scientists, the ability to provide monetary values for ES enables impact of decisions to be considered within the economic driven process that drives decision making (Farber, Costanza and Wilson, 2002; Defra, 2007; Liquete *et al.*, 2016; Ozdemiroglu and Hails, 2016). Whilst attempts at placing a 'total economic value' (TEV) on all ES globally (Costanza *et al.*, 1997; TEEB, 2010; Costanza *et al.*, 2014) have been published and met with criticism (Garwin, 1998; Toman, 1998; Admiraal *et al.*, 2013) the use of valuation methods to assist in decision making has been received more positively (Hanley, Mourato and Wright, 2002; Haines-Young and Potschin, 2009; Hanley and Barbier, 2009; TEEB, 2010; Laurans *et al.*, 2013). In the past the lack of an economic value has led to the environment often not being considered fully at a policy or management level (Daily, 1997; Costanza *et al.*, 1997; TEEB, 2010) with 'no value' equating to 'zero value' (Daily, 1997). Using valuation appropriately and with an understanding of limitations of methodologies used provides a valuable tool to assist in decision making, for examples using cost-benefit transfer and natural capital accounting (Newcome *et al.*, 2005; Fisher, Turner and Morling, 2009; Haines-Young and Potschin, 2009; TEEB, 2010; Laurans *et al.*, 2013; Ozdemiroglu and Hails, 2016).

Placing values on ES is complex as the majority of benefits do not have a traditional market and are considered public goods. Public goods are defined as a good or service that is available to all, and in which the benefit received by an individual does not lessen the availability of the benefit to others (non-rival) (UKNEA, 2011). Multiple people may benefit from a public good at the same time. Classifications of value types have been developed to assist in describing the types of value that individuals or society derive from ES (Figure 1.6, Table 1.3). Provisioning services are typically classified as providing direct use values with estimates being calculated using traditional market prices. Regulating and cultural services typically provide goods that are classified as indirect use or non-use values (Figure 1.6) and provide public goods and services. Methods to value public goods and services, such as revealed or stated preference methods, have been developed and used to place monetary values on ES.

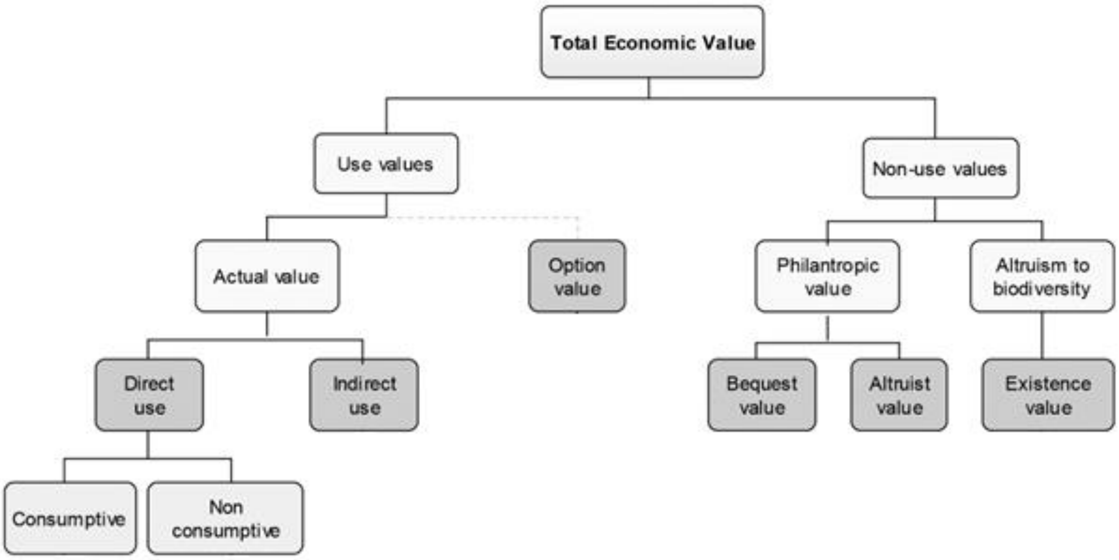


Figure 1.6: Classification of types of value used for valuing the environment (Adapted from TEEB, 2010)

Table 1.3: Types of value used for valuing the environment, definitions and examples (Adapted from TEEB, 2010)

Value Type	Definition	Examples
Use Values		
Direct use value	Results from direct human use of biodiversity	Consumptive: Crops, livestock, fisheries. Non-consumptive: Recreation, spiritual/cultural well-being, education
Indirect use value	Derived from the regulation services provided by species and ecosystems	Pest control, pollination, water regulation and purification
Option value	Relates to the importance that people give to the future availability of an ecosystem service for personal benefit	Plan to visit the rainforest in the future so want to protect it
Non-use values		
Bequest value	Value attached by individuals to the fact that future generations will also have access to the benefits from species and ecosystems (intergenerational equity concerns).	Willingness to protect the rainforest so future generations can use or visit it.
Altruistic value	Value attached by individuals to the fact that other people of the present generation will also have access to the benefits from species and ecosystems (intragenerational equity concerns).	Willingness to protect the rainforests so that native tribes can continue to use and live there.
Existence value	Value related to the satisfaction that individuals derive from the mere knowledge that species and ecosystems continue to exist.	Knowledge that deep sea reefs exist but never likely to visit or use, but still value them

Revealed preference methods rely on using people’s behaviour to infer a value for a given environmental good. They use a market value that is associated with the environmental good(s) of interest. The most common methods are hedonic pricing which uses the housing market, and the travel-cost method, which uses information about the distance, time and cost of an individual to travel to a location. Unlike revealed preference methods which can only be used where there is a market related to the ES of interest, stated preference methods simulate a market through the creation of hypothetical scenarios and therefore can be applied to any ES. Stated preference methods ask people to state what they would be willing to pay for given hypothetical scenarios which involve a change in one or more environmental goods.

When valuing ES careful consideration needs to be given to the selection of the appropriate method and any limitations. Values estimated should be used with an understanding of these limitations, however the limitations should not be used as a reason not to value the environment (Turner *et al.*, 2007a; Haines-Young and Potschin, 2009; Laurans *et al.*, 2013; Ozdemiroglu and Hails, 2016). The use of valuation at a policy level is providing a valuable tool for ensuring the environment is considered within the economic framework employed in decision making.

1.4. Application of the ES Concept

The ES framework is increasingly being integrated into management and policy practice (Laffoley *et al.*, 2004; Beaumont *et al.*, 2008; TEEB, 2010; Mangi *et al.*, 2011; Mace, Norris and Fitter, 2012; Narayan *et al.*, 2016; MacDonald *et al.*, 2017) through tools such as cost-benefit analysis and NC accounting (POST, 2007, 2011; Bolt *et al.*, 2016). Many of these applications rely on the ability to quantify changes in ES and subsequently their monetary value. Private companies, public bodies (e.g. councils) and charities (e.g. RSPB) are utilising the framework to produce NC accounts to assist in the management of their resources (UKNEA, 2014; eftec, 2015; RSPB, 2017; Valuing Nature Network, 2017). The implementation and use of these practices within business, policy and management has raised questions about our ability to accurately assess and quantify such changes (Newcome *et al.*, 2005; Harrison *et al.*, 2014; Díaz *et al.*, 2015; Ozdemiroglu and Hails, 2016). There is a need to ensure that the theoretical conceptual model is grounded in scientific evidence (Beaumont *et al.*, 2007; Laffoley and Grimsditch, 2009). Failure to do this could result in unsustainable decisions with respect to the management of the environment and add to the observed loss and deteriorating state of the natural environment. Concern over the lack of such scientific evidence has been registered within the scientific community and further afield (Laffoley *et al.*, 2004; Beaumont *et al.*, 2007; Fisher, Turner and Morling, 2009; TEEB, 2010; Luisetti *et al.*, 2011a; Paterson, Defew and Jabour, 2012; Díaz *et al.*, 2015) and a need for practical studies investigating the links between NC and economic valuation using the ES framework is needed.

1.5. Case Study: Salt Marshes

Salt marshes are dynamic systems consisting primarily of halophytic herbaceous plants that occur on temperate sedimentary coastlines in the intertidal zone. They are found in sheltered areas where tidal and wind driven currents are low enough to allow the deposition of fine sediment (Adam, 1990). In the UK, most salt marshes are found in the southeast and northwest of England (Figure 1.7). Scotland has comparatively little salt marsh compared to England due to the predominantly exposed rocky shoreline (Burd, 1989).

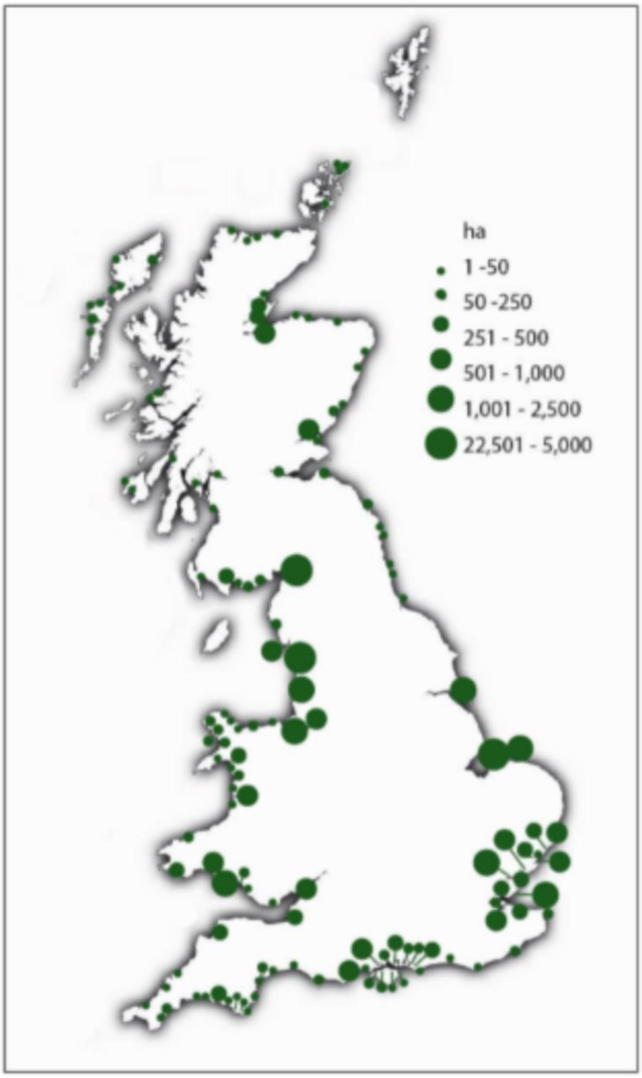


Figure 1.7: The distribution of salt marsh in the UK. The symbol size represents area of salt marsh. (From Maynard 2014, redrawn from Davidson et al., 1991).

Salt marshes are currently declining around the UK primarily as a result of human impacts, principally coastal development, and sea level rise (Boorman, 2003; Hughes and Paramor, 2004; UKNEA, 2011). An estimated 15 km^2 of salt marsh has been lost in the UK since 1992 and a further estimated 0.6 km^2 is currently being eroded each year. In 2003 it was estimated that only 450 km^2 of salt marsh remained in the UK (Boorman, 2003).

Salt marshes are valuable habitats both biologically and economically and provide a wide range of ES (Table 1.4). They are regions of high biodiversity and productivity (Davidson *et al.*, 1991; Doody, 1992, 2004; Adnitt *et al.*, 2007;

Beaumont *et al.*, 2008), with many invertebrate species making them rich feeding grounds for internationally and nationally recognised birds, some of whom also utilise them as breeding sites (Boorman, 2003; Hughes, 2004). They also act as nurseries offering shelter and food for juvenile fish, some of which are important for the commercial fishing industry (Davidson *et al.*, 1991; Doody, 1992). Their ability to dissipate wave energy makes them a valuable form of coastal defence, an ES which has become increasingly valuable due to climate change and sea level rise (King and Lester, 1995a; Möller, 2006; R. a Feagin *et al.*, 2009; Pinsky, Guannel and Arkema, 2013; Möller *et al.*, 2014; Narayan *et al.*, 2016). In some regions, salt marshes are also highly valued areas of pastureland for livestock farming. Additionally, they provide valuable cultural ES owing to their aesthetic properties and wildlife, both of which are important for recreation and tourism industries (Costanza *et al.*, 1997; Millennium Ecosystem Assessment, 2005b; Turner, Georgiou and Fisher, 2008).

Recognition of the ecological importance and economic value of salt marshes, and concern regarding loss, is illustrated though their designation as a key habitat in the European Habitats Directive and the numerous international and national conservation designations that are offered to almost 90% of marshes in the UK (Davidson *et al.*, 1991). As a result, greater importance has been placed on their protection and restoration over the past 30 years with the aim to better manage the remaining marshes and restore or recreate new marshes.

Table 1.4: Ecosystem Services from salt marshes their importance within the UK and globally. Compiled from MA (Millennium Ecosystem Assessment, 2005b) and NEA (UKNEA, 2011)

	National Ecosystem Assessment - UK Importance			Millennium Ecosystem Assessment	
ES Group	**Final Ecosystem Service**	**Goods/Benefits**	**Importance**	**Ecosystem Service**	**Importance**
Provisioning	Crops, plants, livestock, fish etc. (wild & domesticated)	Meat: sheep/cattle	locally high	Food	High
		Wild food: Salicornia, other plants/berries, wildfowl	some	Food	High
		Wool: sheep	locally, some	Fibre, timber, fuel	High
		Genetic resources of rare breeds	some	Genetic materials	Low
	Trees, standing vegetation & peat/other resources	Turf/peat cutting	some	Fibre, timber, fuel	High
		Military use	some		
		industrial use: pipeline landfall/energy generation	some		
Regulatory	Climate regulation	Carbon sequestration	some	Climate regulation	Medium
	Hazard regulation	Sea defence	high	Natural Hazards	High
	Waste breakdown and detoxification	Immobilisation of pollutants	high	Pollution control & detoxification	High
	Purification	Water filtration: surface flow	some	Pollution control & detoxification	High
Provisioning & Regulatory	Wild species diversity including microbes	High diversity, or rare/unique plants, animals, birds and insects	high	Biological regulation	Medium
		Ecosystem specific protected areas	high	Biological regulation	Medium
		Nursery grounds for fish	high	Biological regulation	Medium
		Breeding, over-wintering, feeding grounds for birds	high	Biological regulation	Medium
Cultural	Environmental settings: religious/spiritual, cultural heritage & media	Sites of religious/cultural significance; World Heritage Sites, folklore, TV & radio programmes & films	some	Spiritual & inspirational	High
	Environmental settings: aesthetic/inspirational	Paintings, sculptures, books	high	Aesthetic	Medium
	Environmental settings: recreation/tourism	Many opportunities for recreation including sunbathing, walking, camping, boating, fishing, bird watching etc.	high	Recreational	High
	Environmental settings: Physical/mental health, Security & freedom	Opportunities for exercise, local meaningful space, wilderness, personal space	some	Spiritual & inspirational	High
	Environmental settings: Education/ecological knowledge	Resource for teaching, public information, scientific study	high	Educational	Low

1.6. Salt marsh Restoration

Restoration is essential to achieve ecosystem and NC management goals, reducing biodiversity and habitat loss, and increasing ES provision (Bap, 2008; Bullock *et al.*, 2011; Hobbs *et al.*, 2011; Lotze *et al.*, 2011). In addition, their capacity to provide coastal flood and erosion protection has become a key motivation for their restoration.

Salt marshes can be protected and restored using both passive and active management, a combination of which are generally used for optimal results at a single site (Hughes and Paramor, 2004; Garbutt *et al.*, 2006; Adnitt *et al.*, 2007; Elliott *et al.*, 2007; Wolters *et al.*, 2008; Pétillon *et al.*, 2014; Brady and Boda, 2017). Passive methods require improved enforcement and regulation of coastal activities, such as coastal development and runoff, to ensure that anthropogenic stressors do not adversely impact the salt marsh (Elliott *et al.*, 2007). Improvements in this area have been made since salt marshes were designated as a protected habitat under the European Habitats Directive. Active methods employed to reduce or prevent erosion include the damming and backfilling of creeks, the building of breakwaters outside of a salt marsh, sediment recharge of the marsh, possibly through the use of dredged sediment from the channel, or the reinforcement of banks with sediment fences, and the planting or seeding of vegetation (Morris *et al.*, 2004; Adnitt *et al.*, 2007). In addition, techniques aimed at creating new salt marsh include managed realignment and direct planting. Managed realignment restores former salt marsh on reclaimed land (Adnitt *et al.*, 2007). It involves the building of a new sea wall inland of an existing one, which is then breached, enabling the salt marsh to move inland, as it would naturally, through marine transgression (Figure 1.8). Managed realignment is the most commonly used technique in the UK with the first site being breached in Essex in 1991 (MacDonald *et al.*, 2017).

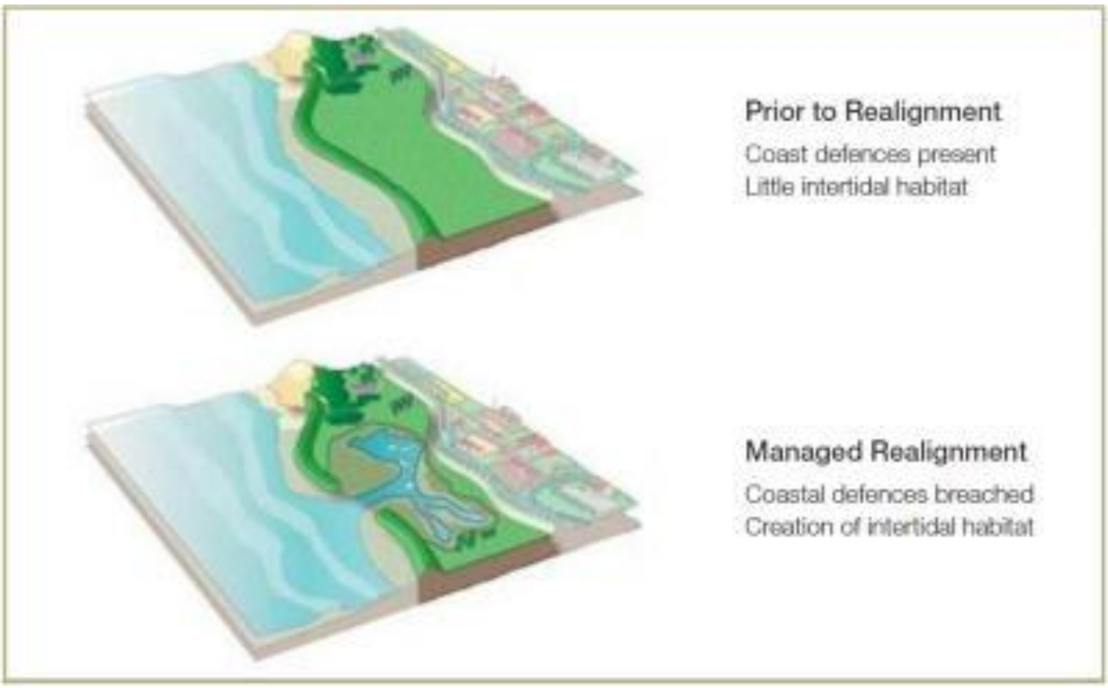


Figure 1.8: Schematic showing stages of managed realignment (ComCoast, 2006)

Monitoring the progress of a restored site is important as an educational resource for future projects, and in understanding its economic value in terms of the capacity to provide ES (Fisher *et al.*, 2008; Luisetti, Turner and Bateman, 2008; Turner, Georgiou and Fisher, 2008). The latter is particularly important for policy and decision makers as it may assist in the selection of different management scenarios through cost benefit analysis.

There is some debate as to whether restored salt marshes can provide equivalent ES compared to natural salt marshes (Zedler and Callaway, 1999; Borja *et al.*, 2010; Lotze *et al.*, 2011; Moreno-Mateos *et al.*, 2012; MacDonald *et al.*, 2017) with uncertainty over the best measures for EF and ES. Studies conducted in the UK at managed realignment sites indicate that the initial colonisation of sites by invertebrates is rapid (months), however for comparable community assemblage to be achieve it took at least 12 years (Garbutt et al. 2006; Hughes et al. 2009). Plant structure and diversity appear to take longer to recolonise managed realignment sites, with the locality of marsh propagules, sediment supply and tidal factors influencing the speed with which this occurs (Wolters *et al.*, 2005; MacDonald *et al.*, 2017). Whilst these studies demonstrate that restoration attempts appear to be developing along a trajectory that could eventually attain comparable levels of EF and consequently ES provision as natural sites, they are largely limited by their focus on individual species or groups of organisms and often the timescale over which they run.

Moreno-Mateos et al (2012) incorporated structural and functional data for restored wetlands in a meta-analysis, and produced trajectories for hydrological, biological and biogeochemical elements (Figure 1.9). Biological structure was 9% more recovered than functional processes, a relationship explained by biological and structural diversity needing to recover before functional processes could develop (Lotze *et al.*, 2011; Moreno-Mateos *et al.*, 2012). Development trajectories of vertebrates and invertebrates recovered more rapidly (5-10 years) than plants (30+ years) (Figure 1.9), with density and richness being used as the response variables (Moreno-Mateos *et al.*, 2012). These trajectories also indicated that structural and functional equivalence had not fully recovered after 100 years, however the declining and limited number of studies after 20 years means that this should be treated cautiously.

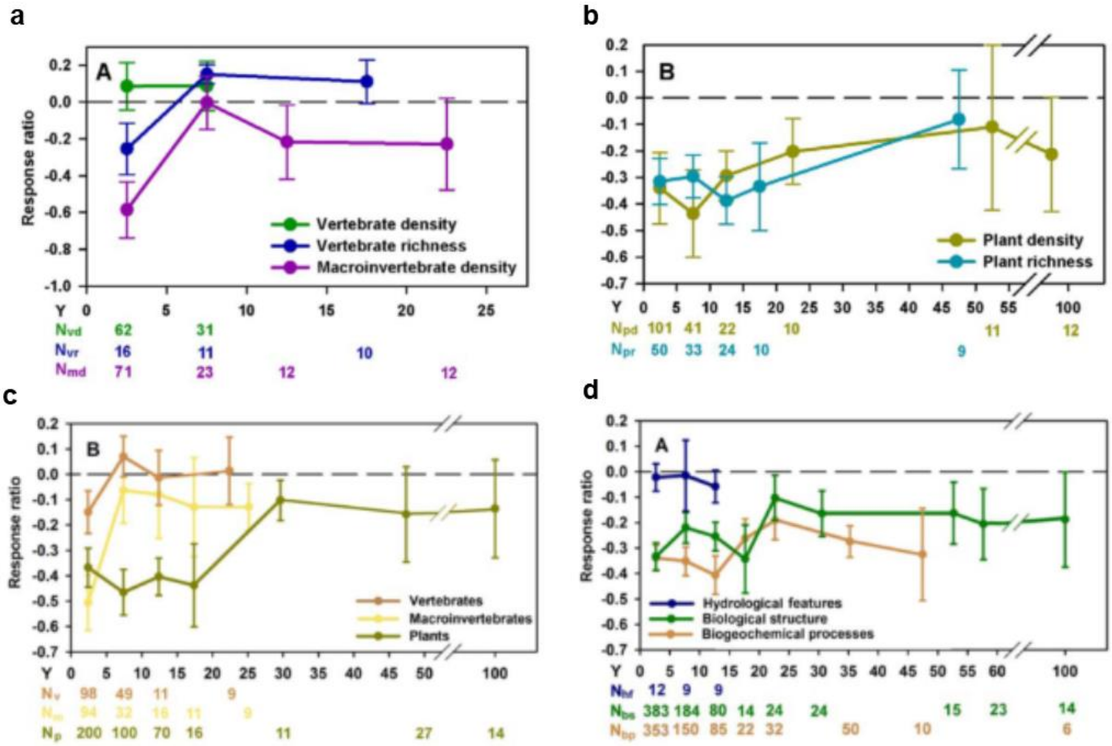


Figure 1.9: Recovery trajectories estimated using meta-analysis of restored wetlands for: a) vertebrates and invertebrates, b) plant structure, c) major biological components of salt marshes, and d) hydrological, biological and biogeochemical elements. Dashed line represent natural reference wetlands (From Moreno-Mateos *et al.*, 2012).

A clear requirement for additional studies, monitoring multiple indicators for EFs over longer time periods is required to fully assess whether restored sites can provide equivalent EF and ES provision. The knowledge of whether restored sites can provide comparable levels of EF and consequently ES, and the length of time this takes is vital information for policy planners, particularly when considering coastal flood management (Spurgeon, 1999; Fisher, Turner and Morling, 2009; Moreno-Mateos *et al.*, 2012).

1.7. Study Site: Eden Estuary, Scotland

The Eden Estuary is located in south-eastern Scotland, north of St Andrews and south of Dundee and the Tay estuary (056° 022’ N 002° 050’ W) (Figure 1.10). It is a tidally driven, small mesotidal bar-built estuary approximately 10.41 km^2 (Eastwood, 1975; Jarvis and Riley, 1987).

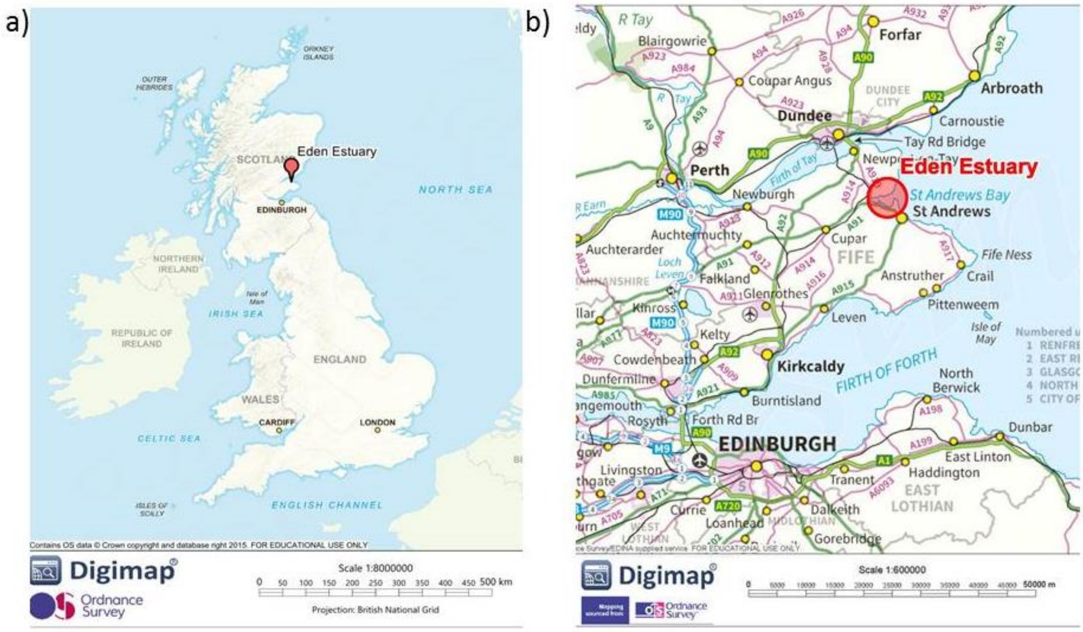


Figure 1.10: The location of the Eden in a) the UK and in detail b) in the south east of Scotland

The tidal influence is approximately 7 km to the west of the mouth of the estuary. The widest point of the estuary is at the mouth and is approximately 2 km. This narrows in the middle of the estuary to approximately 0.5 km due to a well-developed sandy spit and then widens again to 1 km. In the inner estuary, 5 km from the mouth, the estuary narrows at the tidal limit to a width of 80 m to 20 m (Eastwood, 1975). The estuary's main channel meanders north and south and is approximately 9 km long.

The supply of freshwater to the estuary is highly dependent on rainfall (Eastwood, 1975) with the nearest weather station located at the town of Leuchars, recording an average annual rainfall of 691 mm between 1981 – 2010. The 30 km long River Eden provides a mean freshwater input of approximately 2 $m^3\ s^{-1}$ (Jarvis and Riley, 1987) and has two main tributaries, Motray Water and Moonzie Burn (Eastwood, 1975). The estuary is vertically homogenous under average flow conditions and become partially mixed during periods of high rainfall (The Natural Environmental Research Council, 2016). The south shore is more exposed to prevailing winds than the north shore (Eastwood, 1975) and higher wave activity was recorded in winter (Jarvis and Riley, 1987).

The catchment is approximately 307 km^2, most of which is farmland (76%) that is predominantly used for arable farming (The Natural Environmental Research Council, 2016). Several urban areas are also present, the largest of which is St Andrews which has a population of approximately 17,500 (The Scottish Government, 2013). The south shore of the estuary is bordered by high value farmland and the internationally renowned Links Golf Courses including the St Andrews Old Course, one of the most historic and charismatic courses in the world. The north shore is bordered by the small town of Guardbridge, the Leuchars military base and Tentsmuir National Nature Reserve (NNR; Figure 1.11 and 1.12). The latter is an important recreational site in the region with many footpaths and bird hides (Figures 2.2 and 2.3). More than 90% of the estuary is intertidal, with approximately 60% being sand and mudflats (~8 km^2) and just over 1% (0.2 km^2) fragmented salt marsh located along the mean high water mark of both the north and south shores (Strachan, 2013).

Figure 1.11: Aerial image of the south shore of the Eden Estuary and the town of Guardbridge (SERG, 2015)

Figure 1.12: The Eden Estuary showing recreational points of interest (www.tentsmuir.org, 2012)

The Eden has been recognised for its geomorphology and its nationally and internationally important bird populations since 1971. It is a designated Site of Special Scientific Interest (SSSI) (SSSI site reference 596) for its salt marsh, sand dunes, alder-willow swamp woodland, mudflats and the migratory birds. It is part of a larger Ramsar site which includes the Firth of Tay to the north (Ramsar Convention Site UK13018). It also forms part of the European Natura network owing to its designations as a Special Protected Area (SPA) and Special Area of Conservation (SAC), which were designated to protect the nationally and internationally important bird populations that utilise the feeding and breeding grounds and for the common seal population that utilise haul out areas. It has also been designated as a Local Nature Reserve (LNR) since 1978 (Fife Coast & Countryside Trust, 2015).

The estuary is managed locally, although, overall responsibility for the management lies with Scottish Natural Heritage (SNH). The Eden is part of the Tay Estuary and Montrose Basin Local Planning District, but is managed by the Eden Estuary Management Committee, which consists of representatives from the local government, surrounding landowners and interested groups, most of which relate to the recreational use of the area. The Eden is classed as being in an 'unfavourable' state (SNH, 2011), which is largely attributed to the declining state of its habitats.

The south shore of the Eden Estuary is considered a potentially vulnerable area to flooding (SEPA, 2015b). The management plan for the estuary has a 'hold the line' approach (Fife Council, 2012) and currently hard defence structures border approximately 60% of the shoreline. On the south shore, the seaward end of the golf course has a 3 m high gabion wall approximately 0.5 km long that was costly to construct and requires continued maintenance. Along the north shore, adjacent to Leuchars military base, a World War II rubbish tip containing large amount of rubble and inorganic waste was created to act as a sea defence. This is currently being exposed due to erosion and the rubbish is being distributed more widely around the estuary. Sea walls also exist to protect some farmland. Maintaining these defences is costly, offers little in terms of biological value and when breached, the resultant damage is costly to repair. In March 2010, a low pressure system combined with high spring tides caused £75,000 worth of damage to agricultural land on the south shore (pers. comm. R Strachan). The south shore is classed as a potentially vulnerable area to coastal flooding with an estimated £47,000 worth of damage accumulated annually (SEPA, 2015a).

1.8. Salt marshes in the Eden Estuary

Contiguous salt marsh once bordered the Eden but much of it has been buried under artificial structures such as embankments, sea walls and a rubbish tip primarily placed there to act as coastal flood and erosion protection (Crawford, 2008). The remaining salt marsh is fragmented and is considered in an ‘unfavourable condition’ (SNH, 2008) due to the poor representation of upper marsh communities and the extensive loss of the common salt marsh grass, *Pucinella maritima* (SNH, 2008), which is a key species in salt marsh formation (Gray and Mogg, 2001). From the early 1980s it is estimated that approximately 0.2 km^2 of salt marsh have been lost, primarily because of erosion of *P. maritima*, and that only 0.12 km^2 remain (Crawford, 2008; Fife Council, 2008).

One of the main threats to salt marshes currently is considered to be sea level rise, with global measurements showing a rise of 10 – 20 cm during the 20th century (IPPC 2007) and with long-term measurements at Aberdeen recording a rise of around 0.7 mm yr^{-1} (Ball *et al.*, 2008; Werritty, 2012). Concern over the impacts of sea level rise, however, are minimal in the Eden Estuary as they are offset due to the land rebounding at a rate of +1 mm yr^{-1} (Shennan and Horton, 2002) following the last glaciation event, a process known as isostatic rebound (Figure 1.13; Shennan & Horton 2002). In addition, it has been found that where an ample supply of sediment is present, such as in the Eden Estuary (Crawford, 2001; Maynard, 2014), natural salt marshes are capable of keeping pace with sea level rise (French and Burningham, 2003; van der Wal and Pye, 2004).

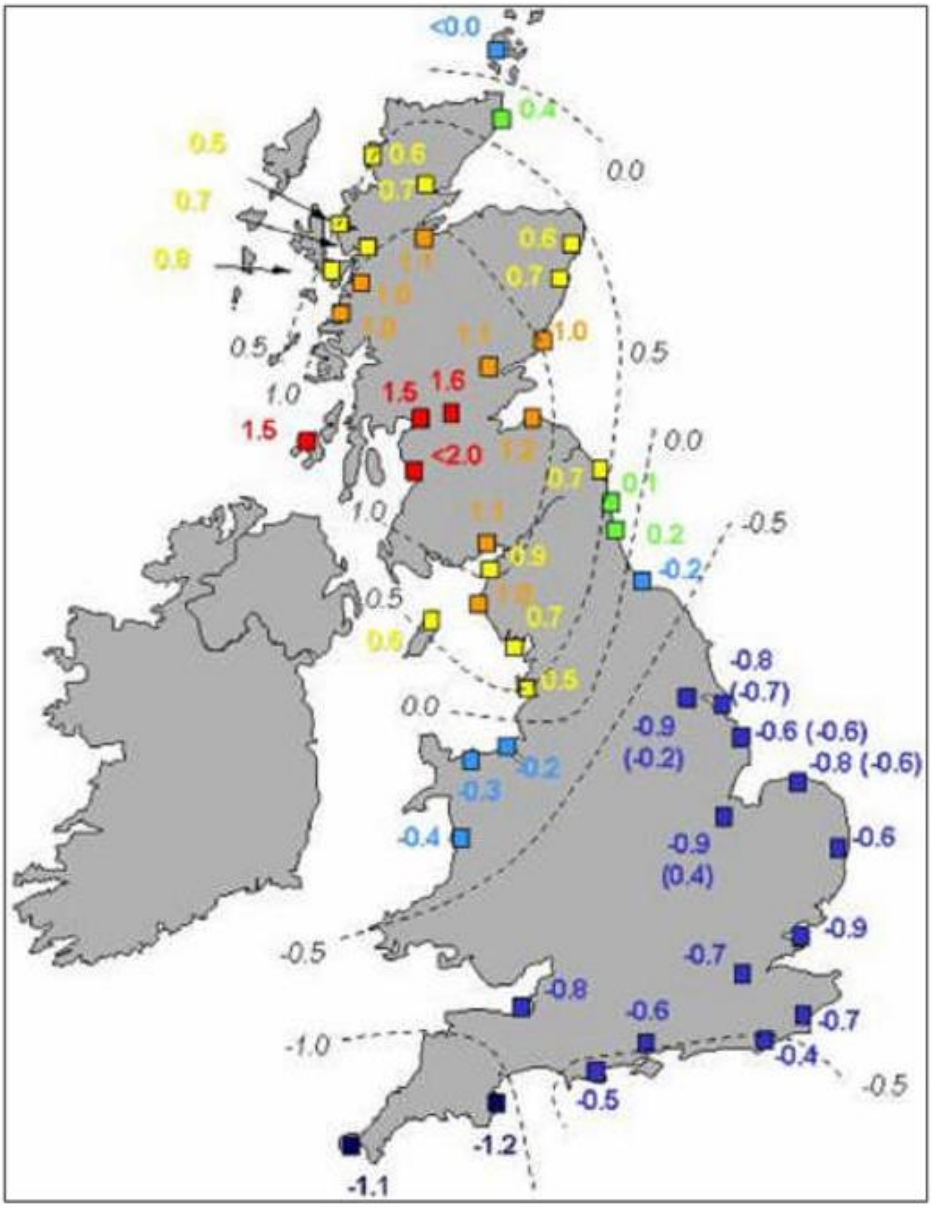


Figure 1.13: Late Holocene relative land-/ sea-level changes (mm yr−1) in Great Britain, positive values indicate relative land uplift or sea-level fall, negative values are relative land subsidence or sea-level rise (from Shennan & Horton, 2002).

Despite the fragmented status of the salt marsh, healthy stands of more brackish swamp and reed bed communities are present in the intertidal zone of the Eden Estuary (Leach and Phillipson, 1985; Hill, 1997; Maynard, 2014). These types of communities are usually not considered to be typical of salt marsh as they are known to prefer higher rainfall and lower salinity areas and are therefore more commonly associated with communities further upstream (Hill, 1997). The increasing levels of precipitation observed in Scotland (Jenkins *et al.*, 2009) combined with the morning haar (sea fog) typical to the east coast of Scotland enables these brackish communities to flourish and become common in the estuarine salt marshes of the east coast of Scotland (Burd, 1989; Hill, 1997). This is confirmed by the abundance of these communities in the larger Tay and Forth estuaries located immediately to the north and south of the Eden Estuary. In the Eden Estuary, increasing levels of freshwater flow have also been recorded (Chocholek, 2013). If these trends continue, the range and extent of these brackish communities could increasingly be providing valuable habitat for coastal protection as they appear to be less vulnerable than *P. maritima* to erosion (Maynard, 2014).

1.9. Restoring Salt Marshes in the Eden Estuary

A pilot project, initiated by Clare Maynard at the University of St Andrews in 2000, aimed to trial different methods of restoring salt marsh within the Eden Estuary. The trials demonstrated that one of the dominant local brackish species, *Bolboschoenus maritimus*, commonly known as the Sea Club Rush, could successfully be transplanted to bare mudflat and accumulate sediment at a greater rate than either natural marsh or bare mudflat (Maynard *et al.*, 2011; Maynard, 2014). Transplantation (Figure 1.14) involves the removal of ‘plugs’, approximately 0.5 m^2 plots from natural healthy stands of the species and relocation. These ‘plugs’ were divided into individual plants or ‘sprigs’ with a pack of mud surrounding them and planted at the new site. Over time these plants have demonstrated the ability to establish and reproduce, developing a root system. Following the success of this pilot project, a transplanting scheme started in 2010 and is currently ongoing (2017). Additional areas totalling approximately 1500 m^2 have been planted on both the north and south shore between 2003 and 2015 (Maynard, pers. comm.). A full review of the restoration work and more detailed methods is available (Maynard, 2014).

Figure 1.14: Stages involved in transplanting salt marsh plants between a natural stand and restoration site.

1.10. Thesis Rationale

Whilst it is apparent that the planted sites in the Eden Estuary are capable of expanding, filling an area, there has been little investigation so far into the return of ecosystem function and community structure associated with recolonisation. As previously discussed, it is important to understand whether the restoration of an area is successful on many levels, including by measuring the functional attributes of the system.

Two key motivations exist for the funders of the restoration work:

1) To create a sustainable coastal defence to protect against flooding (south shore) and erosion (north shore).

2) To provide additional salt marsh habitat.

Utilising the ES framework, the following work addresses the question of whether the planted sites on the south shore have developed along a trajectory that implies they are, or will be, capable of providing equivalent coastal flood protection when compared with the natural stands. In addition, it addresses the question of whether salt marshes are valued as a coastal flood defence by the community local to the Eden Estuary. This interdisciplinary work aims to provide useful information to the managers of the Eden Estuary regarding future coastal flood defence strategies. Additionally, through utilising the ES conceptual framework it will add to the research needed to improve the understanding of the links between biodiversity, EF and ES, providing evidence to assist in our understanding of the practical application of the ES framework.

Chapter 2: Methodology

2.1. Ecological Monitoring

2.1.1. Survey Sites

Monitoring took place at six sites on the South Shore of the Eden Estuary between March 2012 and March 2014. Four planted sites, planted in Spring 2003, 2011, 2012 and 2013 (Table 2.1), and two control sites, a natural stand and a bare mudflat site adjacent to the natural stand were sampled monthly (Figure 2.1). The 2013 site was monitored for a full year before it was planted and acted as a second mudflat control site adjacent to the planted sites until it was planted. Following the planting of the 2013 site an additional bare mudflat control adjacent to the planted sites was established, labelled as 2014.

Table 2.1: Planting dates for planted sites where sampling took place within the Eden Estuary.

Site	Date of Planting
2003	17th – 22nd February 2003
2011	7th – 10th March 2011
2012	11th – 16th February 2012
2013	9th – 15th February 2013

The 2003 site differed from the other planted sites as it was backed by natural salt marsh (Figure 2.2a), primarily *Pucinella maritima*, and a low earth embankment. The remaining planted sites were all backed by a gabion sea wall, with the 2012 site being closest to the natural salt marsh and the 2013 site being furthest away (Figure 2.2b).

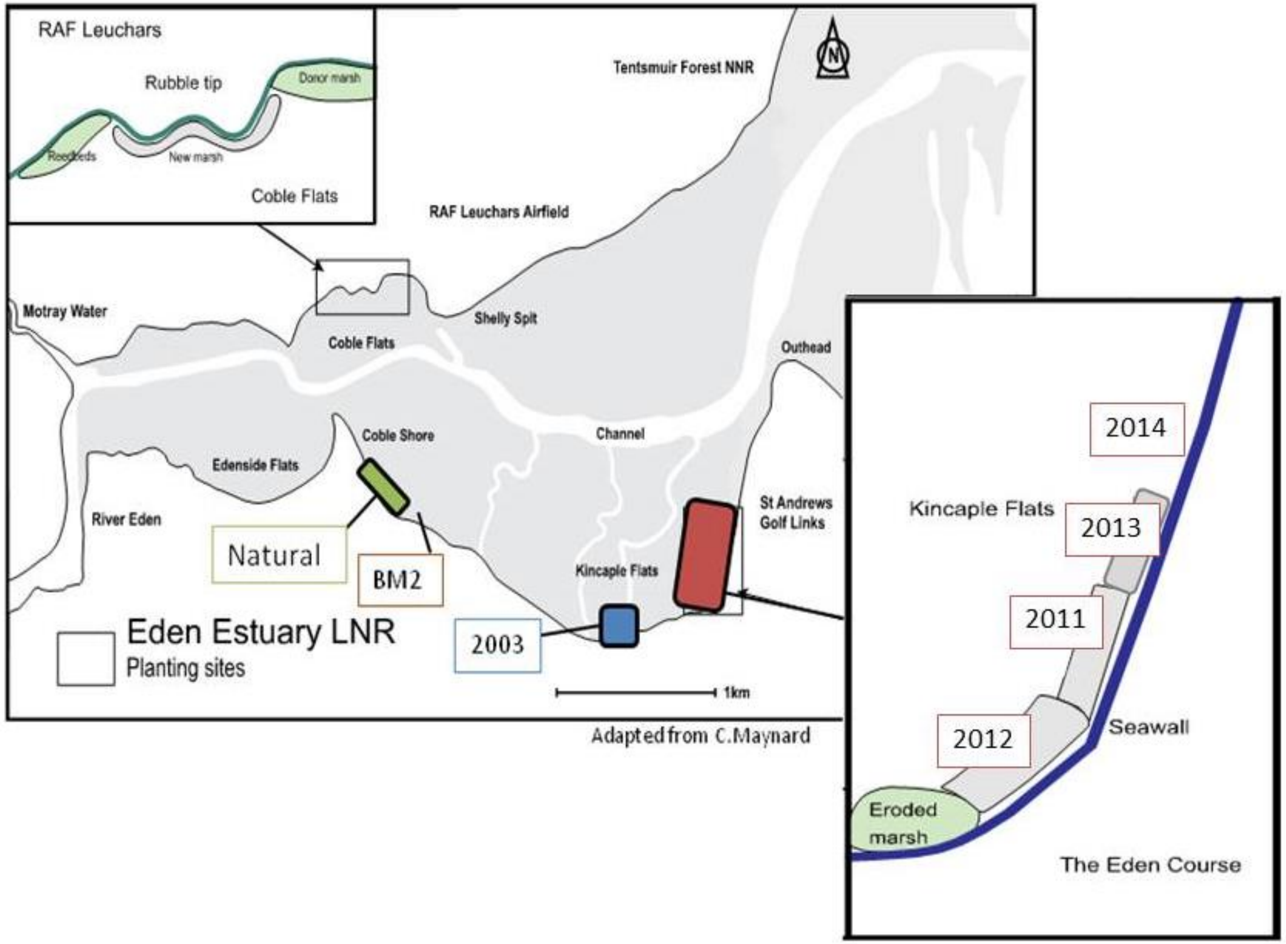


Figure 2.1: The location of each planted site on the south shore of the Eden Estuary, the natural donor stand and bare mud sites (BM2). Figure adapted from Maynard 2014.

a) 

b) 

Figure 2.2: Images of the planted sites on the south shore of the Eden Estuary. a) site 2003 backed by salt marsh and earth embankment and b) sites 2011, 2012 and 2013 backed by a gabion sea wall.

2.1.2. Sampling Regime

Sampling was carried out monthly between March 2012 and March 2013 and again in March 2014. Sampling was timed around spring tides towards the end of each calendar month unless adverse weather prevented this. In these instances, sampling took place as close to the initially allocated time as possible. All sampling and monitoring was conducted at approximately the same tidal level.

2.1.3. Plant Community Monitoring

Plant height and density were recorded every two months at each site. Mean density and height per quadrat were then calculated and used as an estimate of structural complexity and above ground biomass. This is indicative of the ability of the salt marsh to attenuate waves and therefore the ecosystem service of coastal flood and erosion protection (Möller, 2006; Möller *et al.*, 2014).

Plant Height: Four 0.5 m^2 quadrats were randomly placed at each site and the height of all *B. maritimus* shoots whose roots fell within this area were measured to the nearest centimetre. Mean height and range were then calculated.

Plant Density: Calculated by summing the number of *B. maritimus* shoots recorded per quadrat.

2.1.4. Benthic Macrofauna Biodiversity

Macrofauna collection: Four cores of 15 cm depth and 10 cm diameter were randomly sampled every two months from each site to measure macrofaunal biodiversity. Cores were stored at 10 ^{o}C and sieved using a 500 µm diameter mesh within 48 hours of collection. Material that did not pass through the sieve was fixed in 10% formaldehyde. It was then rinsed with water and stored in 80% industrial methylated spirits (IMS) prior to sorting and identification of all organisms' present. All samples were double picked. Three out of the four replicates for each sampling period at each site were stained with Rose Bengal when they were transferred to IMS.

Macrofauna Identification: Organisms were identified to the lowest taxon level possible, usually species, using a binocular dissecting microscope. Species richness and abundance were recorded for each replicate at each site. Examined material was stored in 80% IMS.

2.1.5. Surface Sediment Sampling

Surface sediment characteristics: Four samples were collected every month from each site by freezing the sediment *in situ* using the 'contact core' method (after HiMoM, 2005). Stainless steel cups (Figure 2.3) were placed on the sediment surface and liquid nitrogen was poured into the top compartment freezing the sediment in and surrounding the lower compartment. Excess sediment was removed using a knife, leaving a frozen core of 2 mm depth and 18.5 cm^2 surface area. The core was wrapped in pre-labelled foil and placed in liquid nitrogen until returned to the laboratory to prevent any degradation of the sample. On return to the laboratory all samples were placed in a -80 ^{o}C freezer until analysis to prevent degradation of pigments.

Samples were analysed to determine sediment composition and microphytobenthos (MPB) biomass. Samples were kept cold and in darkness at all times prior to chlorophyll analysis to avoid degradation of pigments. Procedures were based on the HiMoM Protocols (HIMOM, 2005).

Figure 2.3: Contact core used to collect surface sediment samples a) shown in position of use where the top compartment was filled with liquid nitrogen to freeze sediment *in situ;* b) showing underside which was inserted into sediment to collect 2 mm deep core; c) cores *in situ* at 2011 site in the Eden Estuary

2.1.6. Sediment Composition:

Contact core samples were used to determine water content, organic content and grain size.

Water content: Contact cores were weighed (Weight $_{wet}$) and placed into individual pre-labelled bags and dried for 24 h in a freeze drier. Contact cores were then reweighed (Weight $_{dry}$) and the difference used to calculate the percentage water content using Equation 2.1.

$$Water\ Content\ (\%) = \left(\frac{Weight_{wet} - Weight_{dry}}{Weight_{wet}}\right) \times 100$$

Equation 2.1

Organic Matter Content: A subsample (approximately 2.0 g) of the freeze-dried sediment from each contact core and placed in a ceramic crucible. The samples were combusted in a muffle furnace at 450 ^{o}C for 4 h to remove organic matter. Samples were removed and placed in a desiccator at room temperature to minimise exposure to atmospheric moisture and to cool for 1 h before reweighing. The difference in the weight before and after ignition was used to calculate the percentage organic matter using Equation 2.2.

$$Organic\ Matter\ (\%) = \left(\frac{weight\ _{before\ ignition} - Weight_{after\ ignition}}{Weight_{before\ ignition}}\right) \times 100$$

Equation 2.2

Grain Size: Subsamples (approximately 1 g) of the dry contact core sediment from samples collected in March 2012, 2013 and 2014 were sized using a Coulter Laser Granulometer LS230. This measured the size of particles (0.4 – 2000 µm) suspended in water by utilising the diffraction of laser light. Submicron particles (0.4 – 0.04 µm) were also estimated using polarisation intensity differential scattering (PIDS) detector. Samples were suspended in water, passed through a 2 mm sieve and sonicated once in the LS230. Particle size was then estimated, and values were saved on a computer using the LS230 software.

Data was saved as an excel file and processed using the GRADISTAT software Blott, 2010), which allows for multiple samples to be summarised simultaneously. Particle descriptions and size class classifications followed the Wentworth scale (Table 2.2, Figure 2.4).

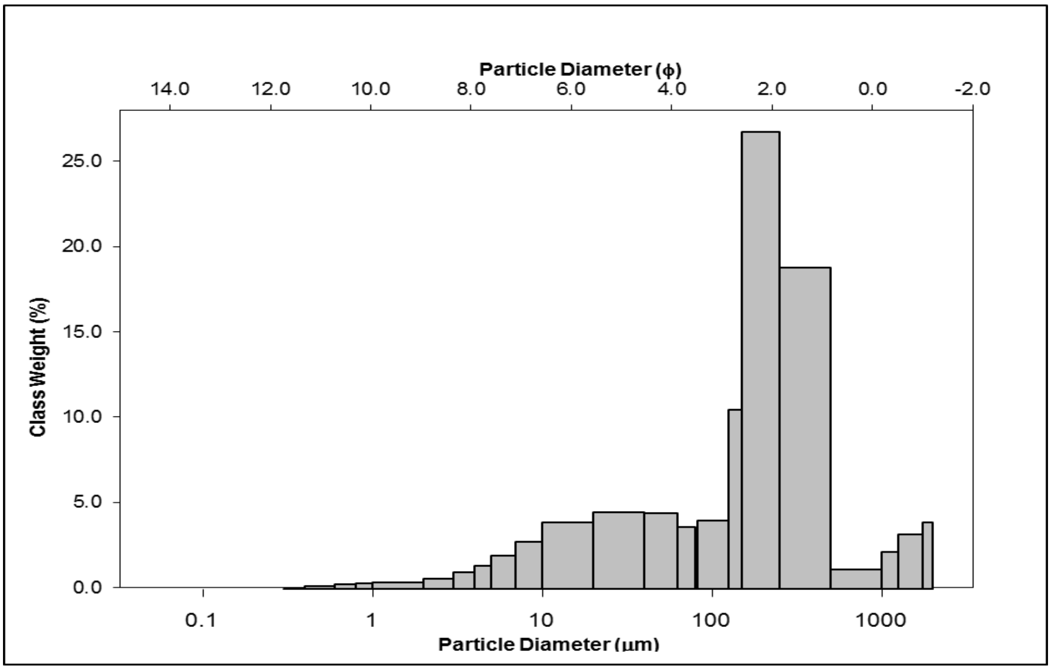


Figure 2.4: Example of grain size distribution output for a single sample produced using the GRADISTAT package (Blott, 2010).

Table 2.2: Size scale adopted in the GRADISTAT program used to calculate particle size distribution. (Modified from Udden (1914) and Wentworth (1922). Taken from (Blott and Pye, 2001).

Grain Size phi	Grain Size mm	Descriptive term	
		Very Large	Boulder
-10	1024		
		Large	
-9	512		
		Medium	
-8	256		
		Small	
-7	128		
		Very small	
-6	64		
		Very coarse	Gravel
-5	32		
		Coarse	
-4	16		
		Medium	
-3	8		
		Fine	
-2	4		
		Very fine	
-1	2		

Grain Size phi	Grain Size mm	Descriptive term	
		Very coarse	Sand
0	1		
	microns	Coarse	
1	500		
		Medium	
2	250		
		Fine	
3	125		
		Very fine	
4	63		
		Very coarse	Silt
5	31		
		Coarse	
6	16		
		Medium	
7	8		
		Fine	
8	4		
		Very fine	
9	2		
		Clay	

2.1.7. Sediment stability

Sediment shear strength and surface cohesion were measured as proxies for sediment stability.

Sediment Strength: A shear vane was used to measure sediment shear strength (Serota and Jangle, 1972; Grabowski, 2014). The vane measures the torque required to initiate failure in the bed. It does not measure surface stability directly, but the undrained shear strength has been used by some authors to estimate the erodibility of the sediment (Mehta & Parchure, 2000) although surface phenomenon such as biofilm development may make this method inaccurate for the calculation of surface stability (Paterson, 1989).

A Pilcon hand held shear van with the 33 mm vane attached was used (Figure 2.5a). Measurements were taken by inserting the vane into the sediment to a depth of 5 cm and applying a constant rotation (approximately 1 rev min^{-1}) until sediment failure. The undrained shear strength was read off the dial (kPa) (Figure 2.5b). Measurements were always taken by the same person to avoid any user bias. Five measurements were made at each site monthly.

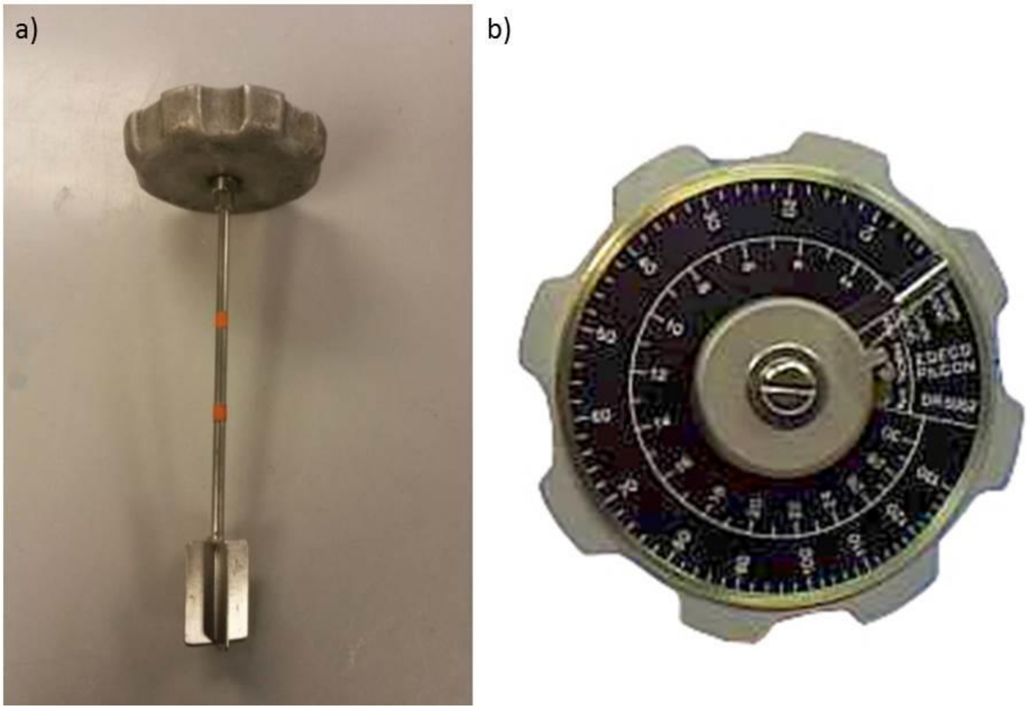


Figure 2.5: Pilcon shear vane a) with 33 mm vane attached and b) face of shear vane where shear strength is indicated.

Sediment Cohesion: A cohesive strength meter (CSM) was used to measure small scale variations in surface sediment stability *in situ* (Paterson, 1989; Tolhurst *et al.*, 1999; Vardy *et al.*, 2007). This method is considered more accurate for measuring surface stability that the use of a shear vane as it accounts for surface phenomenon such as biofilms. Five replicates were recorded at each site and an average calculated.

A CSM fires a pressurised water jet though a water filled chamber at the sediment surface, increasing the jet pressure incrementally. When the firing pressure is great enough to disturb and suspend the sediment an infra-red sensor in the water chamber detects a reduction in the light transmission. A 10% reduction in light transmission, which equates to an erosion rate of 0.01 kg m^{-2}, is commonly taken to be the critical eroding pressure (Tolhurst et al. 1999; Figure 2.6, 2.7). The data are downloaded from the CSM and the critical erosion pressure is calculated. The pressure can then be converted to horizontal shear stress using a calibration equation.

Figure 2.6: The cohesive strength meter (CSM) a) *in situ* at the bare mud site in the Eden Estuary; b) erosion chamber *in situ*; c) transparent erosion chamber in operation with coloured jet of water.

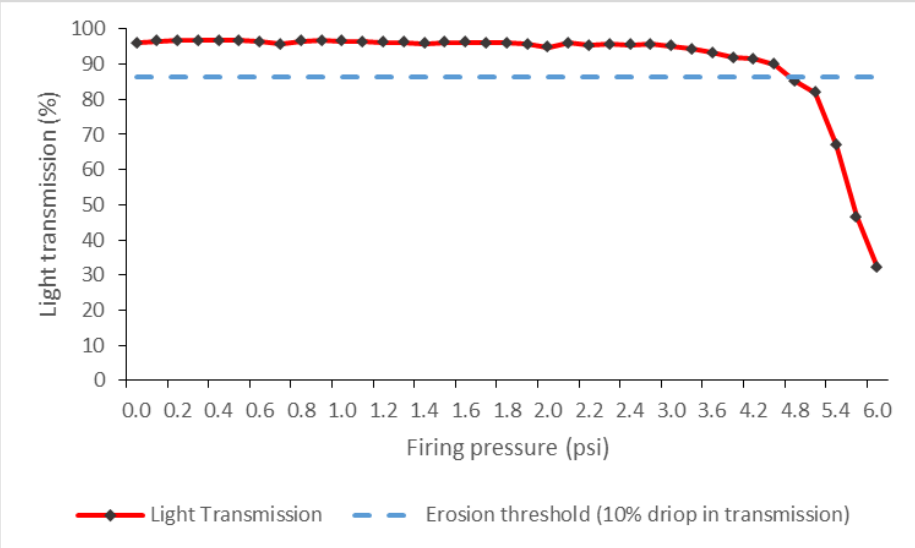


Figure 2.7: Example of data recorded using the CSM illustrating the 10% drop in light transmission accepted to be the critical erosion threshold (Tolhurst et al., 1999)

Wet Bulk Density: WBD is a measure of sediment consolidation (bulk material/space occupied) that is negatively correlated to sediment erodibility (Grabowski, Droppo and Wharton, 2011). The denser the sediment the more compacted it is and therefore less susceptible to erosion.

Contact cores were weighed (Weight $_{wet}$) prior to freeze drying. The volume of the contact core was calculated, and Equation 2.3 was used to determine the bulk density.

$$Bulk\ Density\ (g\ cm^{-3}) = \frac{sediment\ weight_{wet}\ (g)}{Volume\ (cm^3)}$$

Equation 2.3

2.1.8. Microphytobenthos (MPB) Biomass

MPB organisms contain chlorophyll that can be used as a biomass proxy (Tolhurst *et al.*, 2005). Chlorophyll was extracted from contact cores collected at each site.

2.1.8.1. Chlorophyll

Chlorophyll Calibration: The spectrophotometer was calibrated against a known concentration of chlorophyll$_a$ prior to processing of the samples. A stock solution was made using 1 mg spinach diluted in 250 ml of 90% acetone. Serial dilutions of 4, 2, 1, 0.5 and 0.25 mg l^{-1} were made and stored in the dark and below 4 ˚C. The spectrophotometer was used to measure the solution absorbance at 662 and 750 nm and the chlorophyll concentration was calculated using the equation 2.4.

$$Chlorophyll\ (mg\ l^{-3}) = \frac{[A_{662}] - [A_{750}]}{E} \times 1000$$

Where, E is the extinction coefficient for *chlorophyll$_a$*

Equation 2.4

Chlorophyll Extraction: Sediment samples were kept cold and in the dark at all times to avoid degradation of pigments. A subsample of the freeze dried sediment was weighed from each contact core (approximately 0.3 g) into a centrifuge tube and 4 ml of 90% acetone (V_e) added. The samples were placed in an ultrasound bath containing -4˚C saltwater for 90 min. They were then placed in a freezer at -20˚C for 48 h to allow for the extraction of the pigment, removed after 24 h and mixed for 20 s in a vortex mixer. This process obtains a 90% extraction efficiency (Wiltshire *et al.*, 2000).

Chlorophyll Analysis: Samples were kept cold and in the dark at all times to avoid degradation of pigments. The samples were removed from the freezer and centrifuged for 3 min at 1300 rpm to separate out the supernatant from the sediment. The supernatant was pipetted into a cuvette and analysed using a spectrophotometer. Absorbance was read using a Biomate 5 spectrophotometer at 630, 647, 664 and 750 nm. Chlorophyll content was calculated using Equation 2.5 and converted to concentration using the Equation 2.6 as this accounts for variation in the mass of the core (Tolhurst *et al.*, 2005).

$$Chlorophyll_a\ (\mu g\ g^{-1}) = \frac{(11.85 \times (abs_{664} - abs_{750}) - 1.54 \times (abs_{647} - abs_{750}) - 0.08 \times (abs_{630} - abs_{750}) \times V_e}{Sample\ weight\ (g)}$$

Where, abs_x = the absorbance and x nm wavelength
V_e = the extraction volume

Equation 2.5

$$Chlorophyll_a\,(mg\,m^{-2}) = \frac{Chlorophyll_a\,(\mu g\,g^{-1}) \times {}^{A}\!/_{B}}{1000}$$

Where, A is the dry weight of the whole contact core (g)
B is the surface area of the contact core (m^2)

Equation 2.6

2.1.8.2. Extracellular Polymeric Substances

Extracellular polymeric substances (EPS) are secreted by the MPB during photosynthesis and are used in their locomotion and help prevent desiccation. EPS forms a matrix that stabilises the surface and helps prevent erosion of the sediment (Underwood and Smith, 1998; Yallop, Paterson and Wellsbury, 2000). They also influence the carbon budget within estuaries. Diatom EPS consists primarily of carbohydrates, uronic acids and to some lesser extent proteins (Yallop *et al.*, 1994; Decho, 2000; Underwood and Paterson, 2003).

The phenol-sulphuric acid Dubois assay (DuBois *et al.*, 1956) was used to quantify the colloidal carbohydrate concentration of the surface sediment. An adaptation of the LOWRY Method (Raunkjaer et al., 1994, Frølund et al., 1996) was used to assess protein concentration of the surface sediment. Both are generally accepted to correlate well with the eukaryotic microbial biomass of the sediment (Underwood, Paterson and Parkes, 1995) and consequently can be used as a proxy for MPB biomass. The Dubois assay is a colorimetric assay that is sensitive to most constituents of EPS including sugars, methylated sugars, neutral and acidic polysaccharides (Decho, 1990). The LOWRY method is sensitive to the proteins within the EPS.

Acid Wash: All equipment used for analysing carbohydrate and protein content was acid washed prior to analysis. Glassware was placed in a 10% HCl bath for 24 h. It was then removed and rinsed three times with distilled water before being oven dried and sealed to ensure it was not contaminated.

EPS extraction: A subsample of the freeze dried contact core sediment (~50 mg) was added to 3 ml distilled water and centrifuged for 25 mins at 1500 rpm to extract the colloidal carbohydrate and protein and pelletise the sediment. The supernatant was then removed using a pipette for quantification of carbohydrate and protein.

Carbohydrate analysis: 1 ml of the supernatant was added to a glass test tube followed by 1 ml of 5 % phenol and 5 ml of concentrated sulphuric acid (ratio of 1:1:5). Samples were mixed for 20 s (vortex mixer) and then left to react for 35 min under a fume hood to allow the reaction to progress and the resultant colour to develop. Samples were then decanted into 3 ml cuvette and absorbance read at 486.5 nm against a blank solution of 1 part distilled water: 1 part phenol: 5 parts sulphuric acid. Colloidal carbohydrate content was calculated using Equation 2.7 and then converted to concentration using Equation 2.8. Reporting data as concentration accounts for variation in water content and bulk density unlike content which does not (Tolhurst, Riethmüller and Paterson, 2000).

$$\text{Colloidal carbohydrate } (\mu\text{g g}^{-1}) = \frac{{(Abs\ -\ c)}/{m} \times V_e}{sample\ weight\ (g)}$$

Where, Abs = absorbance recorded at 486.5 nm
c = intercept of the calibration curve line
m = gradient of calibration curve
V_e = volume of water used to extract EPS / volume of extractant used in analysis

Equation 2.7

$$Colloidal\ Carbohydrate\ (mg\ m^{-2}) = \frac{Colloidal\ carbohydrate\ (\mu g\ g^{-1}) \times {A}/{B}}{1000}$$

Where, A is the dry weight of the whole contact core (g)
B is the surface area of the contact core (m^2)

Equation 2.8

Carbohydrate Calibration: Glucose standards from serial dilutions of a stock solution (0, 2, 5, 10, 20, 50, 100, 200 µg ml^{-1}) were analysed using the phenol – sulphuric acid assay as described above. Regression analysis was used to create a calibration curve for absorbance and carbohydrate concentration (Fig 2.9). A new set of standards and calibration was completed for each batch of samples processed.

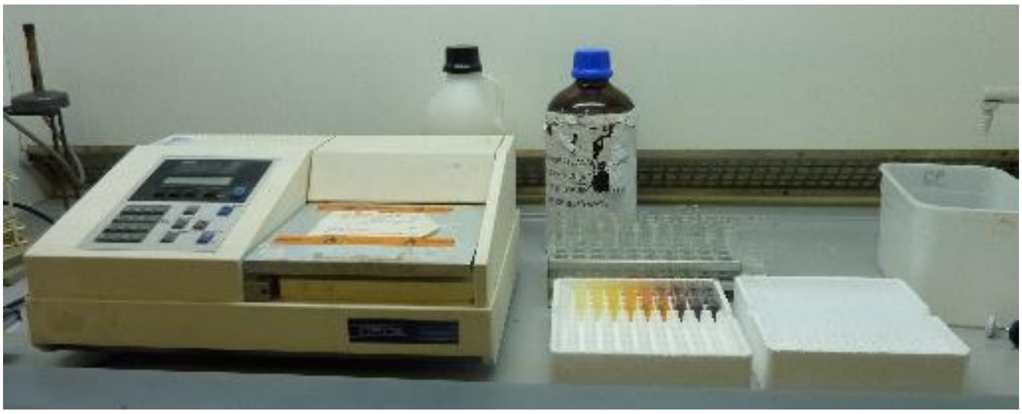


Figure 2.8: Equipment for carbohydrate analysis with serial dilutions of standards

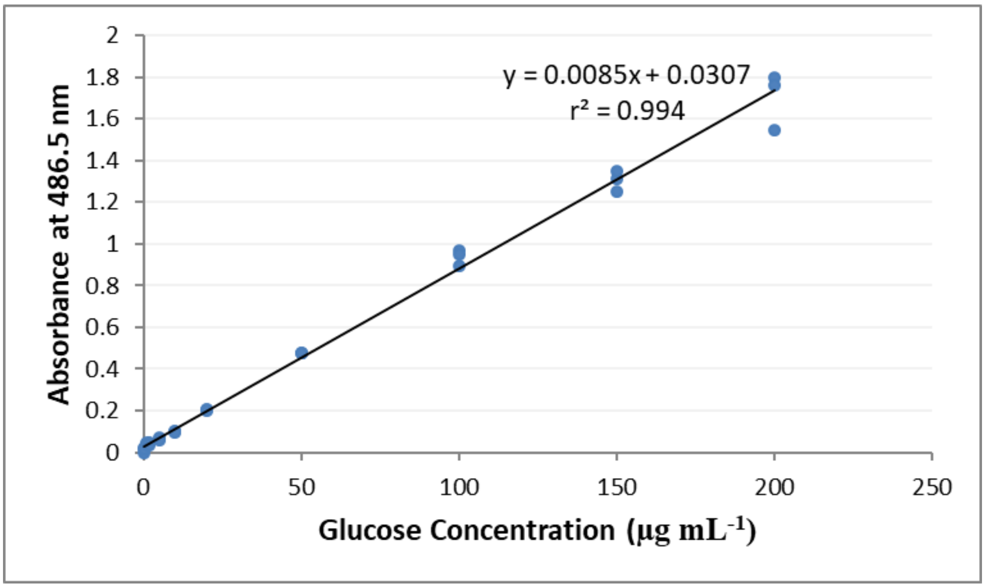


Figure 2.9: Example of a calibration curve for carbohydrate analysis.

Protein analysis: Reagents were made up (Table 2.3) with reagent 4 being freshly made for each batch of samples. In a test tube, 0.75 ml of the supernatant was added to 0.75 ml 2% SDS and 2.1 ml reagent 4 and placed in a 30°C water bath for 15 min and vortexed every 5 min. 0.3 ml of reagent 5 was then added and samples were mixed and returned to the water bath for 45 min and vortexed every 5 min during this period to allow for colour to develop. Sample absorbance was measured at 750 nm using a spectrophotometer. Protein content was calculated using Equation 2.9 and then converted to concentration using Equation 2.10.

Table 2.3: Reagents used in the LOWRY method to quantify protein concentration in EPS.

Reagent 1	143 mM NaOH, 270 mM Na2CO3 = 0.572 g NaOH + 2.8617 g NaCO3
Reagent 2	57 mM CuSO4 = 0.0909 g CuSO4
Reagent 3	124 mM Na-tartrate = 0.285 g Na-tartrate/10 ml
Reagent 4	Reagent 1, 2, 3 in ratio 100:1:1 (volumes)
Reagent 5	Folin Reagent 5:6 (volume) distilled water

$$\text{Protein } (\mu\text{g g}^{-1}) = \frac{{(Abs\ -\ c)}/{m} \times V_e}{sample\ weight\ (g)}$$

Where, Abs = absorbance recorded at 750 nm
c = intercept of the calibration curve line
m = gradient of calibration curve
V_e = volume of water used to extract EPS/ volume of supernatant used in analysis

Equation 2.9

$$Protein\ (mg\ m^{-2}) = \frac{Protein\ (\mu g\ g^{-1}) \times {A}/{B}}{1000}$$

Where, A is the dry weight of the whole contact core (g)
B is the surface area of the contact core (m^2)

Equation 2.10

Protein Calibration: Bovine albumin serum standards from serial dilutions of a stock solution (0, 10, 30, 50, 70, 100, 120, 150 µg ml^{-1}) were analysed using the LOWRY method as described above. Regression analysis was used to create a calibration curve for absorbance and protein concentration (similar to Figure 2.13). A new set of standards and calibration was completed for each batch of samples and every time a new reagent 4 was made up.

2.1.9. Statistical Analysis

The majority of analyses were performed using the R statistical software version 3.2.5 (R Core Team, 2016) through the R Studio interface (R Studio Team, 2015). A variety of statistical tests were performed and are described in greater detail in each chapter. In all instances where appropriate the assumptions of tests were assessed: homogeneity of variances, normality and outlying data points (Zuur, Ieno and Smith, 2007). Where data violated the assumptions for parametric tests, non-parametric alternatives were used.

PRIMER v6 software (Clarke & Gorley, 2006) and PERMANOVA+ (Anderson et al., 2008) were used to calculate diversity indices and carry out multivariate analyses to examine the benthic community structure. Again, assumptions were checked prior to continuing with statistical tests.

2.2. Economic Valuation

A choice experiment (CE) was used to assess the willingness to pay (WTP) for coastal flood defences in the Eden Estuary, Fife. The survey was approved by the University Teaching and Research Ethic Community (UTREC) at the University of St Andrews (Appendix A).

The estuary is currently considered at risk from flooding and erosion and management plans enforce a 'hold the line' approach that aims to maintain the current coastline without loss of any land to erosion (SEPA, 2015a, 2016). This requires the maintenance of existing defences and potentially the creation of new defences.

2.2.1. Background Theory of Choice Experiments

CE are a type of "stated preference" methodology commonly used for valuing non-market goods such as those provided through ecosystem services (Luisetti, Turner and Bateman, 2008; Ozdemiroglu and Hails, 2016). Stated preference methods rely on asking people about their willingness to pay (WTP) or willingness to accept (WTA) a change in "a good" (Louviere, Hensher and Swait, 2000; Hanley and Barbier, 2009), in this case coastal flood defence.

CE present people with a set of scenarios with differing levels of the attributes that contribute to the good in question, known as a choice set. By asking people to choose their preferred option from the choice set we can infer which attributes are important and significantly influence choices relating to that good. An option for status quo or no change should always be included as not all attributes may be valued. If price or cost is included as an attribute associated with each scenario we are also able to infer what people are WTP for a change in an individual attribute or for changes in several attributes simultaneously (Louviere, Hensher and Swait, 2000; Hanley and Barbier, 2009; Hensher, Rose and Greene, 2015).

The CE method is underpinned by Random Utility Theory (McFadden, 1974) and Lancaster's 'characteristics theory of value' (Lancaster, 1966) which states that a good is made up of a number of characteristics or 'attributes', and that estimating the value of the good can be best explained by assessing the demand for the attributes (Louviere, Hensher and Swait, 2000; Hanley and Barbier, 2009; Hensher, Rose and Greene, 2015). Random utility theory is used to model people's behaviour.

The utility, *U*, that an individual, *n*, gains is dependent on their choice of alternate, *j*. The utility function that describes this is composed of a deterministic component, V, and a stochastic component, ε. It is assumed that the choice made by the individual will depend on the attribute, q_i, and the socio-economic characteristics of the individual, y_n, such as their income.

$$U_{jn} = V\left(y_n,\ q_j\right) + \ \varepsilon_j$$

Equation 2.11

It is assumed that an individual will always select the alternative that will give them the greatest utility. The probability of choosing alternative *i* over alternative *j* from the choice set, C which contains all alternatives can be described as follows

$$p\ (i\ |C) = p\ \{\ V_{ni} +\ \varepsilon_{ni}\ >\ V_{nj} +\ \varepsilon_{nj}\ ;\ j \in C\ \}$$

Equation 2.12

Different models have been developed to describe people's behaviour, each rely on different assumptions about the distribution of the random terms.

The conditional logit model (CLM) is the principal model that is typically used for analysis of CE data (Hensher, Rose and Greene, 2015). It assumes that all error terms are independently and identically distributed (IID) over all alternatives and individuals meaning that there are zero covariances or correlations between the unobserved effects and that the distribution of the unobserved effects are all the same. Consequently the probability of choosing one alternative over another is completely independent of the utility of other alternatives (independence of irrelevant alternative, IIA assumption) (Hensher, Rose and Greene, 2015).

The probability that an individual, *n* choses a particular option, *i* over all other options, *j* can be modelled as follows

$$p_n(choose\ i) = \frac{\exp(\mu_n V_{nj})}{\sum_{j \in C} \exp(\mu_n V_{nj})}$$

Equation 2.13

Where V is the deterministic and observable component within the random utility model and μ is a scale parameter, typically normalised to 1, relating to the variance of the error component of the random utility model.

The deterministic part of the model, *V*, is typically assumed to be a linear function of the choice attributes, X.

$$V = \alpha + \beta_1 X_1 + \cdots\cdots \beta_n X_n + \beta_c X_C$$

Equation 2.14

There are n + 1 attributes and for each attribute the model estimates a coefficient value, β which shows the effect that a change in the attribute level has on utility, moderated by the scale parameter, μ, and whether people prefer an increase or decrease in each attribute. Where cost is incorporated into the model as an attribute, X_c, the coefficient, β_c, shows the effect of a change in price of an option and the likelihood of choosing that option. The implicit price, which is the WTP for a marginal change in a given attribute, can be estimated by dividing the coefficient for an attribute β_x by the cost coefficient β_c. The model also uses maximum likelihood to estimate the probability of the parameters and consequently establish whether they are significant (Hensher, Rose and Greene, 2015).

The IID assumption of the CLM do not allow for preference heterogeneity between the respondents as it assumes that all respondents place the same value on the attributes. This is commonly found not to be true and violation of IID can lead to inaccurate coefficient values (Louviere, Hensher and Swait, 2000; Hanley, Mourato and Wright, 2002). Models with greater flexibility that allow for people to value attributes to differing levels, relaxing the IID assumption, have been developed. A commonly used approach for CE is the mixed logit model (MLM) which allows for variations in preferences across respondents by estimating a mean effect and standard deviation for each attribute. It estimates random parameters, β_n, which vary among the population with a density function of $f(\beta_n \mid \theta)$ (Hensher, Rose and Greene, 2015). Common distributions used for θ are normal and lognormal. Normal distributions do not constrain the signs of the parameter estimate and in some cases can lead to counter-intuitive results, such as a positive β_c. In these cases a lognormal distribution is commonly used to restrict the parameter estimates to the same sign, however, due to the infinite tail of this distribution calculating WTP estimates is problematic (Hensher, Rose and Greene, 2015).

2.2.2. Experimental Design

It is important when designing the CE that the choice sets, and their attributes are credible and believable to the participants. Careful consideration of the design of the CE and subsequent testing is strongly advised (Hensher et al., 2005). A more detailed description of how the CE was designed is presented in chapter 5.

Survey Question: The aim of the study was to establish how much people were WTP for coastal flood defences in the Eden Estuary and whether this value varied given the type of flood protection offered in the scenario.

Attribute Selection: Following interviews with the main stakeholders and managers within the estuary, attributes were chosen that provided relevant and realistic management scenarios. The two attributes selected were the type of coastal defence protection and the type of land being protected. A cost attribute of an increase in council tax was also incorporated.

Choice Set Design: A labelled design was used with each choice set consisting of the same 4 hypothetical management scenarios instead of generic labels. The labels represented the alternatives for the first attribute, type of coastal flood defence, and remained constant for all choice cards: hard defences, soft defences, combined defences and no change. During analysis this design allows the estimation of alternative specific constants (ASCs) for each management scenario to be estimated and compared to a baseline. Careful consideration and explanation of the alternatives were provided in the background information prior to completing the survey to minimise violation of the IID assumption (Hensher, Rose and Greene, 2015). No change represented the *status quo* and was taken to be the current situation within the Eden and had a zero cost; this is the scenario to which all other scenarios would be compared to. All other labels offered an increase in the coastal flood protection and an increase in council tax cost associated with them.

The extent of additional flood protection offered in each scenario was divided between the second attribute: the types of land being protected. The alternatives included were representative of those present in the Eden Estuary: housing/property, farmland and golf courses. The extent of each was represented as percentage of coastline protected. For housing and property in the Eden Estuary this is approximately 50%, for farmland 25% and golf courses 25%. An example of a choice set is shown (Figure 2.10).

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **40%** of coastline	Protect **30%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
 Farmland	Protect **15%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **25%** of coastline	Protect **0%** of coastline	Protect **15%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£175**	**£175**	**£75**	**£0**

Figure 2.10: Example choice set from main survey.

The statistical package NGENE was used to create the choice sets using the attributes, their alternatives and associated levels as described (Table 2.4). Three blocks of eight choice sets were specified (Table 2.5). The output with the lowest d_{error} and no dominance was selected.

The levels for cost were representative of the cumulative cost over a three year period (i.e. total cost of £120 was equivalent to £40 per year over a three year period).

Table 2.4: Attributes, their alternatives and levels used in choice experiment to value coastal flood defence in the Eden Estuary.

Attribute	Alternatives	Levels
Type of flood protection	Hard/Sea Wall	Labelled alternatives
	Soft / Salt marsh	
	Combined / Sea wall and salt marsh	
	Status Quo/No Change	
Type of land being protected	Property	0%, 10%, 20% ,30%, 40%, 50%
	Farmland	0%, 5%, 10%, 15%, 20%, 25%
	Golf Courses	0%, 5%, 10%, 15%, 20%, 25%
Cost	Council Tax	£120, £225, £360, £525, £675, £900

Survey Design: The survey was built using the questionnaire software developed by surveygizmo.com. This software allows for surveys to be completed online, as an offline electronic copy or as a hard copy.

The survey consisted of a background information video, a warm up question, a block of eight choice set questions chosen at random from the three available questions relating to the participants use of the Eden Estuary and finally some socio-demographic questions. It had an estimated completion time of 12-14 minutes including the time taken to watch the background information video (6 min 23 sec).

Full information relating to the development of the survey design is discussed and presented in chapter 5. A full copy of the background video script and survey questions can be found in appendices A and B.

Table 2.5: Experiment design output of choice sets using NGENE for valuing coastal flood defence in the Eden Estuary.

Choice set	**Hard**					**Soft**					**Combined**					**Block**
	Farm	Golf	Property	Price	**Price/3**	Farm	Golf	Property	Price	**Price/3**	Farm	Golf	Property	Price	**Price/3**	
8	25%	20%	10%	120	**40**	0%	10%	30%	675	**225**	10%	5%	30%	900	**300**	**1**
9	15%	10%	20%	900	**300**	25%	20%	10%	360	**120**	0%	5%	50%	120	**40**	**1**
10	5%	25%	30%	360	**120**	5%	5%	40%	360	**120**	20%	5%	10%	360	**120**	**1**
11	15%	0%	20%	675	**225**	0%	15%	20%	675	**225**	25%	25%	30%	120	**40**	**1**
12	20%	5%	20%	900	**300**	5%	15%	50%	120	**40**	20%	20%	20%	675	**225**	**1**
13	20%	0%	30%	525	**175**	15%	25%	40%	525	**175**	0%	15%	0%	225	**75**	**1**
14	10%	10%	50%	675	**225**	25%	20%	0%	120	**40**	0%	10%	30%	675	**225**	**1**
21	5%	25%	40%	360	**120**	20%	0%	10%	225	**75**	15%	20%	30%	900	**300**	**1**
2	0%	25%	30%	225	**75**	25%	10%	40%	525	**175**	20%	0%	10%	360	**120**	**2**
3	20%	15%	30%	900	**300**	15%	0%	50%	225	**75**	10%	25%	0%	225	**75**	**2**
4	5%	20%	20%	525	**175**	15%	10%	0%	360	**120**	20%	15%	50%	360	**120**	**2**
7	0%	0%	10%	120	**40**	10%	25%	30%	900	**300**	25%	20%	40%	525	**175**	**2**
15	20%	0%	40%	360	**120**	15%	5%	20%	900	**300**	5%	25%	0%	225	**75**	**2**
18	25%	15%	40%	120	**40**	0%	20%	10%	525	**175**	5%	5%	0%	525	**175**	**2**
19	0%	10%	0%	120	**40**	20%	25%	40%	525	**175**	15%	10%	40%	900	**300**	**2**
20	0%	5%	10%	525	**175**	10%	15%	0%	675	**225**	25%	20%	50%	120	**40**	**2**
1	10%	25%	50%	225	**75**	15%	5%	10%	360	**120**	5%	15%	0%	675	**225**	**3**
5	25%	20%	40%	360	**120**	5%	0%	30%	225	**75**	10%	20%	10%	675	**225**	**3**
6	15%	0%	10%	225	**75**	10%	20%	30%	900	**300**	15%	25%	40%	525	**175**	**3**
16	10%	5%	50%	525	**175**	20%	20%	0%	120	**40**	10%	10%	30%	900	**300**	**3**
17	15%	10%	50%	675	**225**	5%	25%	20%	225	**75**	15%	0%	20%	360	**120**	**3**
22	25%	5%	0%	225	**75**	10%	10%	10%	900	**300**	0%	25%	50%	225	**75**	**3**
23	10%	15%	20%	900	**300**	20%	25%	30%	675	**225**	5%	0%	50%	120	**40**	**3**
24	5%	15%	0%	675	**225**	0%	15%	50%	120	**40**	25%	10%	20%	525	**175**	**3**

2.2.3. Data Collection

Participants completed the survey online where it was accessed through webpages created using the University of St Andrews website. The target area for participants was northeast Fife (Figure 2.11). The survey was launched in March 2014 and remained open for approximately a year. Initially participants were found through advertising locally and social media. Posters were placed in local meeting venues such as community halls, shops, transport hubs, schools and gyms. Presentations were given at local community and council meetings asking the representatives present at the meetings to promote the survey. It was also advertised using Twitter and Facebook and sent to several mailing lists locally.

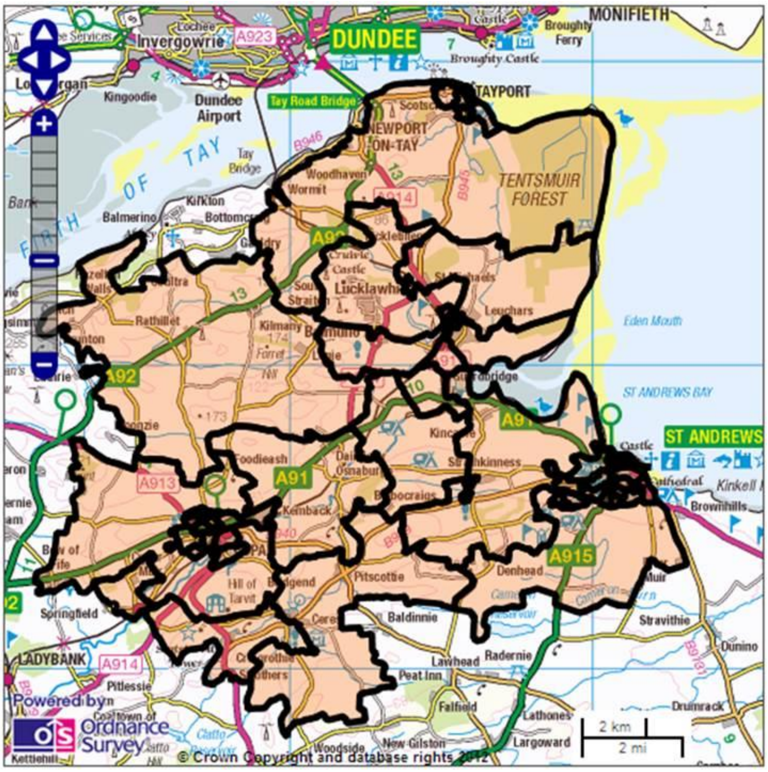


Figure 2.11: The CE coverage. The shaded areas in northeast Fife. represents target sampling zone for survey data collection (From www.sns.co.uk).

After an initially good rate of response (March 2014 –June 2014), numbers started to decline, and alternate methods were used to ensure that the necessary number of responses was reached. In January 2015, a web broadcast was sent to 10,000 e-mail addresses within the Fife region. A follow up broadcast was sent in February 2015. In addition to this a mail shot was sent to 300 homes in the northeast Fife region inviting homeowners to complete the survey online. An incentive in the form of an entry into a prize draw for online shopping vouchers was offered upon completion of the survey.

2.2.4. Statistical Analysis

CLM and MLM were used to estimate the respondents' preference for the different types of flood defence and the type of land to be protected. The coefficients from these models were then used to calculate the WTP and marginal willingness to pay for coastal flood defences and their associated attributes. Modelling was conducted using STATA (STATA Corp., 2015).

Chapter 3: Ecosystem Function in Restored Salt Marshes, Eden Estuary

3.1. Introduction

Over the past three decades there has been increasing interest in the methods by which we can better maintain and restore existing UK salt marshes. This has been in recognition of loss, both historical and ongoing, and the declining condition of existing salt marshes threatening the provision of valuable ecosystem services (Brooke *et al.*, 2000; Pethick, 2002; Millennium Ecosystem Assessment, 2005b; Adnitt *et al.*, 2007; Gedan, Silliman and Bertness, 2009; Pasupalati *et al.*, 2017). Understanding of the value of salt marshes and concern over their deteriorating state is illustrated through their designation as a key habitat in the European Habitats Directive, along with numerous other international and national conservation designations, which protect over 90% of salt marshes in the UK (Davidson *et al.*, 1991; Boorman, 2003; Adnitt *et al.*, 2007).

Whilst the term ‘ecosystem services’ was not well established prior to the publication of the first Millennium Ecosystem Assessment reports in 2003, the concept that ecosystems are a valuable resource for humans has been presented and generally accepted for decades (Daily, 1997; Costanza *et al.*, 1997; TEEB, 2010; UK National Ecosystem Assessment, 2011a). When monitoring ecosystems, many goals are now based around an ecosystem service framework and this is increasingly being integrated into management and policy (Beaumont *et al.*, 2007; TEEB, 2010; Mace, Norris and Fitter, 2012; Barbier, 2016; MacDonald *et al.*, 2017) through tools such as cost benefit analysis and natural capital accounting. Consequently, the need to monitor ecosystem services over time is essential to assess the success or failure of restoration from a target-driven management perspective (Bayraktarov *et al.*, 2015; Zhao *et al.*, 2016). This, however, can often prove challenging as it is not possible to measure many ecosystem services directly and consequently, proxies are often used (Hooper, Chapin III and Ewel, 2005; Solan *et al.*, 2006; Beaumont *et al.*, 2008; Haines-Young and Potschin, 2009; Harrison *et al.*, 2014). To establish suitable proxies, a thorough understanding of the ecosystem components, environmental processes and interactions and driving forces or pressures is required.

The relationships between organisms, processes, functions and services are complex. One or more processes contribute towards an ecosystem function, and one or more functions, which offer a benefit to humans, contribute to an ecosystem service (Haines-Young and Potschin, 2010; Paterson *et al.*, 2011) (Figure 3.1). Processes and functions may contribute to more than one service and they are all influenced by the contextual biological, chemical and physical factors. Therefore, understanding the functions and the underlying processes that occur within an ecosystem is essential to define ecosystem services (Spurgeon, 1999; Haines-Young and Potschin, 2009; TEEB, 2010; Luisetti *et al.*, 2011b; UKNEA, 2011) and to select the best variables (proxies) to measure during monitoring. This process is complex and may vary depending on the location and desired outcomes of the project (Solan *et al.*, 2006; Beaumont *et al.*, 2007; TEEB, 2010).

Careful thought must be given when selecting appropriate measures of ecosystem functions and an understanding of their limitations is needed. Unfortunately with many restoration projects, monitoring is poorly planned and consequently assessing the success or failure of a project is limited (Brady and Boda, 2017). When designing monitoring it is also important to consider monetary and time limitations, the repeatability of the measurement and the impact of the monitoring itself (Bayraktarov *et al.*, 2015). Destructive techniques should be avoided where possible and kept to a minimum when unavoidable so as not to impact the success of the restoration. The measures should be suitable to assess whether the motivation and desired goals set for the restoration of the site have been attained. It is important to ask the correct questions and design logistically acceptable monitoring to properly address them.

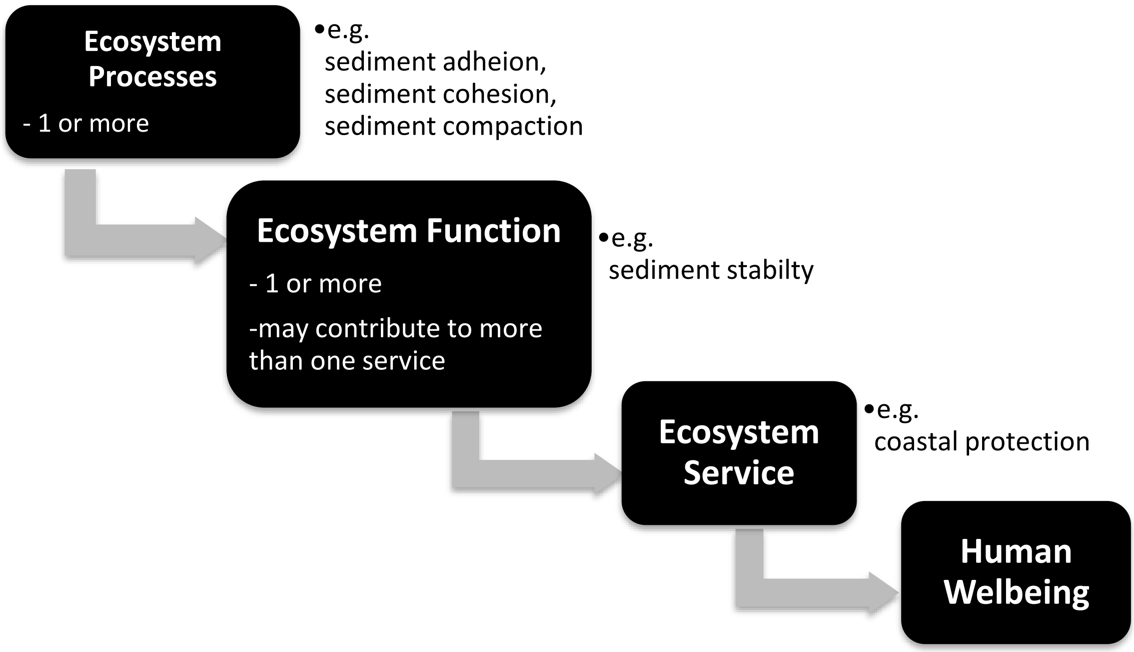
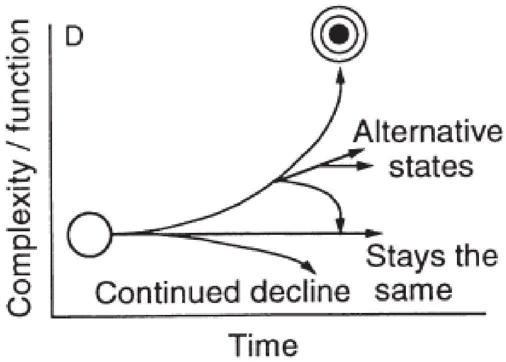


Figure 3.1: Relationship between ecosystem processes, ecosystem functions, ecosystem services and human well-being (modified from Haines-Young & Potschin, 2009).

Restoration of ecosystems is not always successful, and some restored sites may not return to a state comparable to other healthy natural sites. Instead, an alternative stable state may be reached (Figure 3.2a), which could provide a different (lesser) suite of ecosystem functions and services (Zedler and Callaway, 1999; Borja *et al.*, 2010; Lotze *et al.*, 2011; Moreno-Mateos *et al.*, 2012). Plotting the development of ecosystem functions, or the proxies for them, against time, allows the production of a hypothetical pathway for recovery termed a 'trajectory' (Figure 3.2b) (Simenstad and Thom, 1996; Zedler and Callaway, 1999). This typically requires data to be collected over an extended period (at least 10 years) from restored sites and control sites. Longer time series such as these are not common due to monetary limitations, the lack of long-term monitoring projects, and suitable foresight ahead of management (Zedler and Callaway, 1999; Moreno-Mateos *et al.*, 2012; Brady and Boda, 2017). Whilst less informative, shorter data sets can still be used to provide valuable information on recovery trajectories of ecosystem functions (Turner *et al.*, 2007b). The ability to assess datasets to provide estimates of functional equivalency i.e. when an ecosystem service attains a comparable level to that found in a natural site, are of great assistance to managers. A knowledge of how long it will take for a restored salt marsh to act as an effective coastal flood defence, for example, allows managers to value prospective flood defence scenarios through cost-benefit analysis (Spurgeon, 1999; Turner *et al.*, 2007b; Narayan *et al.*, 2016).



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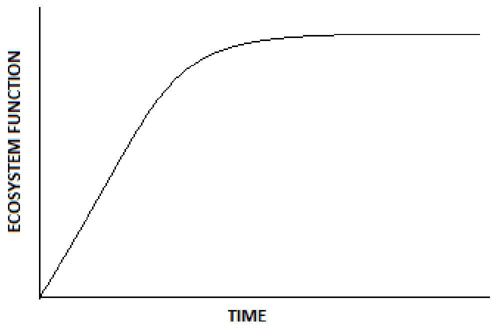


b

Figure 3.2 a) Hypothetical trajectories of ecosystem function through time from degraded ecosystem (open circle) to natural ecosystem conditions (bullseye), or other options (Zedler and Callaway, 1999) b) Hypothetical development trajectory of an ecosystem function through time.

The principal reasons for restoring salt marshes varies depending on the motivations behind the project and the stakeholders involved. Two drivers behind restoration projects are: (a) creating a more economically sustainable form of coastal defence and; (b) providing habitat compensation to replace existing habitat lost to development (Adnitt *et al.*, 2007; Brady and Boda, 2017). In addition to coastal defence from flooding and erosion and habitat provisioning, several other ecosystem services are provided by restoring salt marshes. The importance of the ES provided will vary dependent on the stakeholders and the projects aims. In the Eden Estuary, coastal defence and habitat provision are key motivators. Whilst land owners are primarily interested in achieving more economically sustainable coastal flood defences, they are also interested in defences ability to provide additional habitat (pers. comm. Strachan, Cunningham and Moir). Stakeholders such as SEPA and SNH have the priorities for these ecosystem services reversed. Their primary focus is the restoration of habitat, however where possible they choose to utilise methods which also assist in mitigating against the flooding and erosion of prime land providing benefits for nature and protection for society (pers. comm. Strachan, Cunningham).

3.2. Aim of chapter

Experimental sites in the Eden Estuary have demonstrated that plants can successfully be transplanted and form stable communities that expand in range and accumulate sediment in amounts comparable to that of naturally occurring sites (Maynard *et al.*, 2011). In this chapter the success of these planted sites in terms of ecosystem functioning is examined, focussing principally on those ecosystem functions contributing to the service of coastal flood defence. On the south shore where the experimental sites are located this is one of the main goals of the restoration project.

A number of proxies for ecosystem function were investigated to assess seasonal and annual patterns and trajectories comparing natural sites (bare mud and salt marsh) and restored sites:

1. **Plant height and density** - Plant height and density are important measures of salt marshes' ability to attenuate wave energy (Möller, Spencer and French, 1996; R. a Feagin *et al.*, 2009; Shepard, Crain and Beck, 2011; Möller *et al.*, 2014; Narayan *et al.*, 2016) and therefore can be used as a proxy for coastal defence.

2. **Trapping and stabilising sediment** - The ability of a salt marsh to act as a coastal defence is linked to its ability to keep pace with sea level rise by trapping and stabilising sediment. Maynard et al (2011) established that the restored salt marshes are capable of accumulating sediment at a rate comparable to, or greater than that of the natural salt marsh. The stability of this sediment can provide useful information with respect to the success of the restored salt marshes ability to act as a coastal flood defence.

3. **Biogenic stabilisation** - Sediment stability is known to be influenced by sediment characteristics and the microphytobenthos (MPB) community (Underwood, Paterson and Parkes, 1995; Yallop, Paterson and Wellsbury, 2000; Jesus *et al.*, 2009; Grabowski, Droppo and Wharton, 2011). The presence of MPB is known to stabilise sediment through the production of extracellular polymeric substances (EPS) (Austen, Andersen and Edelvang, 1999; Black *et al.*, 2002; Tolhurst, Gust and Paterson, 2002; Wotton, 2004; Tolhurst, Consalvey and Paterson, 2008; Grabowski, Droppo and Wharton, 2011; Malarkey *et al.*, 2015; Chen *et al.*, 2017). EPS consists primarily of carbohydrates, uronic acids and to some lesser extent proteins (Underwood and Paterson, 2003). The EPS forms a matrix which binds sediment through adhesion and traps water in micropores, stabilising the sediment surface and help prevent erosion of the sediment (Underwood and Smith, 1998; Yallop, Paterson and Wellsbury, 2000; Wotton, 2005; Grabowski, Droppo and Wharton, 2011) and subsequently facilitates the colonisation of mudflats by plants (Underwood 1997; M. L. Yallop et al. 2000; Little et al., 1992). Chlorophyll *a* content of surface sediment is commonly used as a proxy for MPB biomass and colloidal carbohydrate and protein concentrations of surface sediment as proxies for extracellular polymeric substances (EPS) and hence stabilisation.

4. **Physical context.** -The MPB community and erosion of sediment is known to be influenced by sediment characteristics including water content, grain size, density and organic content (Underwood, Paterson and Parkes, 1995; Yallop, Paterson and Wellsbury, 2000; Jesus *et al.*, 2009; Grabowski, Droppo and Wharton, 2011).

3.2.1. Specific aims and related hypothesis

The aims and related hypothesis for this Chapter have been developed in accordance with the above proxies and are

Aim 1: To examine plant structure in natural and planted marshes

H_0: The planted marshes will not show any significant difference in plant height or density from natural marshes.

Aim 2: To examine sediment stability in natural and planted marshes

H_0: The planted marshes will not show any significant differences in sediment stability from natural marshes or bare mud flat.

Aim 3: To examine sediment composition in natural and planted marshes

H_0: The planted marshes will not show any significant difference in grain size, water content, mud content, organic matter content or wet bulk density from natural marshes or bare mud flat.

Aim 4: To examine MPB and EPS biomass in natural and planted marshes

H_0: The planted marshes will not show any significant difference in surface sediment Chlorophyll *a* or EPS concentration from natural marshes or bare mud flat.

3.3. Methodology

3.3.1. Sample Collection

Measurements were taken, and samples collected at the natural donor marsh site (natural), a bare mud site (bare mud) and sites that were planted in 2003, 2011, 2012 and 2013 (Figure 2.1). Site 2013 was bare mud at the beginning of the study until it was planted in February 2013.

Plant structure measurements (Section 2.1.3) were collected every two months between March 2012 and March 2013. Additional monitoring of the plant community between November 2011 and March 2012 was also incorporated into the analysis (McLachlan, 2012). Surface sediment samples were collected monthly (Section 2.1.5) and processed in order to quantify water content, organic content, bulk density, colloidal carbohydrate, protein and chlorophyll *a* concentration, grain size and sediment type (Section 2.1.6 and 2.1.8). *In situ* measurements for sediment stability (Section 2.1.7) were also taken monthly between March 2012 and March 2013. Additional data using the raw data files for erosion threshold from a previous study was incorporated for December 2011 – March 2012 (McLachlan, 2012).

Measurements and sample collections were made at an additional time point in March 2014. This time point was combined with those collected in March 2012 and March 2013 to provide a three-year time series.

3.3.2. Statistical Analysis

All analyses were performed using the "R" statistical platform version 3.2.5 (R Development Core Team, 2016) through the R Studio interface (version 0.99.896). Pearson (parametric) or Spearman's (non-parametric) correlations were used to investigate patterns present between variables as appropriate.

Differences in each variable between and within sites and years for the three-year dataset (March 2012, 2013 and 2014) were investigated using a two-way ANOVA with interaction. Year was treated as a random factor and site as a fixed factor. Where the interaction was found not to be significant, the simplified model was used following standard backward elimination protocols and use of the minimum adequate model (MAM) (Zuur, Ieno and Smith, 2007). A *post hoc* Tukey test was applied where significant differences were found. Where data did not meet the assumptions for ANOVA (normality and/or homogeneity of variances) non-parametric Kruskal Wallis tests were used with *post hoc* Dunn's test. Due to there being no non-parametric test comparable to a two-way ANOVA with interactions, the interaction term was not statistically tested for non-parametric variables.

Generalised Additive Models (GAM) were used to evaluate differences over time for the seasonal (18-month and 13-month) time series (November 2011 – March 2013 and March 2012 - March 2013 respectively). Generalised Additive Models (GAM) are flexible regression models that can cope with non-normal distributions and heteroscedasticity. They are increasingly used to model spatial and temporal trends in ecological data (Wood, 2006) as they enable the estimation of non-linear smooth functions to describe the relationship between covariates and response variables of interest. GAM models were estimated using the “mgcv” package (v1.8.14, Wood) in R. The default settings using thin plate regression splines were estimated using penalised least squares method with smoothing parameters. GAM models were tested with and without an interaction between date and site. The model with the highest deviance explained and lowest AIC was selected for each variable.

This method was chosen for plant height and density over a general linear model (GLM) due to the expected non-linear pattern observed because of seasonal growth and die back of the plants (Zuur, 2012). The surface sediment characteristics and microphytobenthic community data had a high level of natural variability that created ‘noise’ in the model. In order to lessen this ‘noise’ and account for any seasonal differences, data was blocked into seasons (Table 3.1) and GAM models were used to evaluate differences between seasons and sites for each response.

Table 3.1: Seasons allocated to data for the 13-month time series.

Season	Date
Spring 2012	March 2012 – May 2012
Summer 2012	June 2012 – August 2012
Autumn 2012	September 2012 – November 2012
Winter 2012/13	December 2012 – February 2012
Spring 2013	March 2012

All models were checked for autocorrelation and, where appropriate, an autocorrelation term was incorporated. In all these instances, the autocorrelation term did not contribute significantly to the model and the simpler model was used (MAM). Some variables were found to have unequal variances between levels of site or season, which may violate assumptions for the model. In these instances, a weighted variance function was incorporated that allows different levels of a factor to have different variance structures.

3.4. Results

3.4.1. Plant Community Structure

Mean plant height was calculated per quadrat with four replicates at each site and each time point. For conciseness, this is now referred to as "plant height" and reference to mean plant height refers to the mean plant height per site, which is the mean of the four quadrats.

3.4.1.1. Correlation

A significant strong positive correlation was found between plant height and plant density for all data collected ($r_s = 0.72$, $p < 0.001$; Figure 3.3).

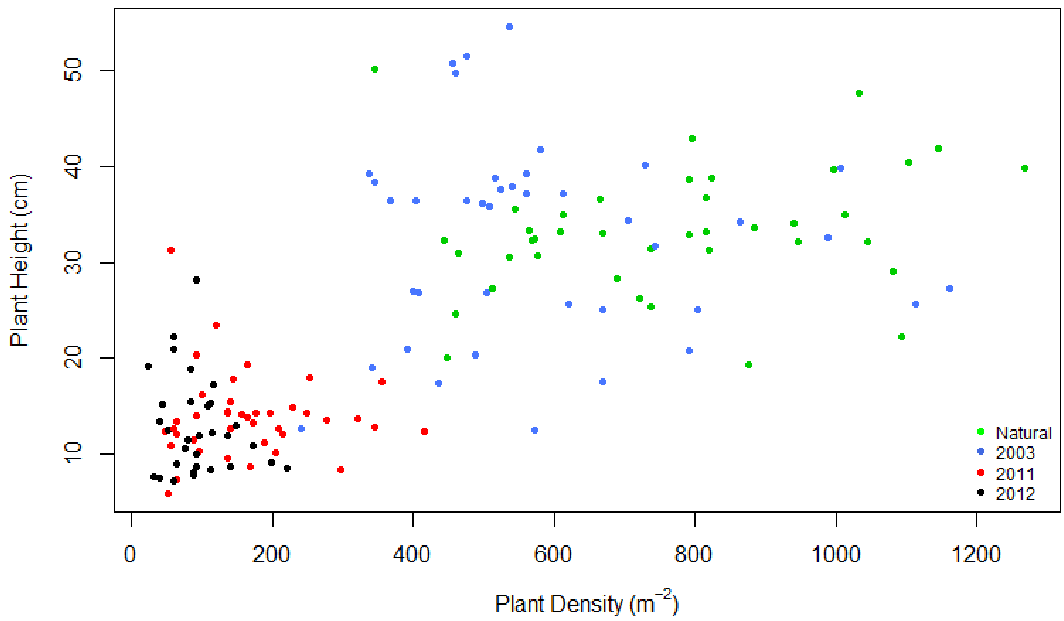


Figure 3.3: Bi-plot of plant height and mean plant density at all sites across all years ($r_s = 0.72$, $p < 0.001$).

3.4.1.2. Plant Height – Three-Year Time Series

A significant interaction was found between site and year for plant height ($F_{6,36} = 8.789$, $p<0.001$; Figure 3.4).

The oldest planted site (2003) was the most comparable to the natural site; and both increased in height from years 2012 to 2013 (19.0 and 11.6 cm, respectively) and changed little between 2013 and 2014 (variation of 1.4 and -0.9 cm, respectively). A *Post hoc* Tukey test confirmed that unlike years 2013 and 2014, the plant height in year 2012 was significantly different for site 2003 from all other sites, including the natural site (Figure 3.4c). Plant height at the youngest planted sites, 2011 and 2012, varied little between years (variation of 3.2 and 0.9 cm, respectively) and plants were shorter than at either the natural or the oldest planted site (2003). A *post hoc* Tukey's test confirmed that the natural and 2003 sites both had significantly taller plants than the 2011 and 2012 sites (Figure 3.4b). The natural and 2003 sites did not differ significantly from one another and neither did the 2011 and 2012 sites.

Table 3.2: Summary statistics for plant height, expressed in cm: mean and standard deviation for all sites and years sampled within the Eden estuary.

	Year			
Site	**2012**	**2013**	**2014**	**All years**
Natural	24.7 ± 4.7	36.3 ± 4.0	37.7 ± 3.8	32.9 ± 7.2
2003	17.4 ± 3.6	36.4 ± 3.5	35.5 ± 3.4	29.8 ± 9.6
2011	10.2 ± 1.6	12.8 ± 0.3	13.4 ± 0.9	12.1 ± 1.8
2012	10.5 ± 5.8	10.1 ± 2.3	10.5 ± 3.8	10.4 ± 3.4
All sites	15.7 ± 7.2	23.9 ± 13.1	24.3 ± 13.0	21.3 ± 11.9

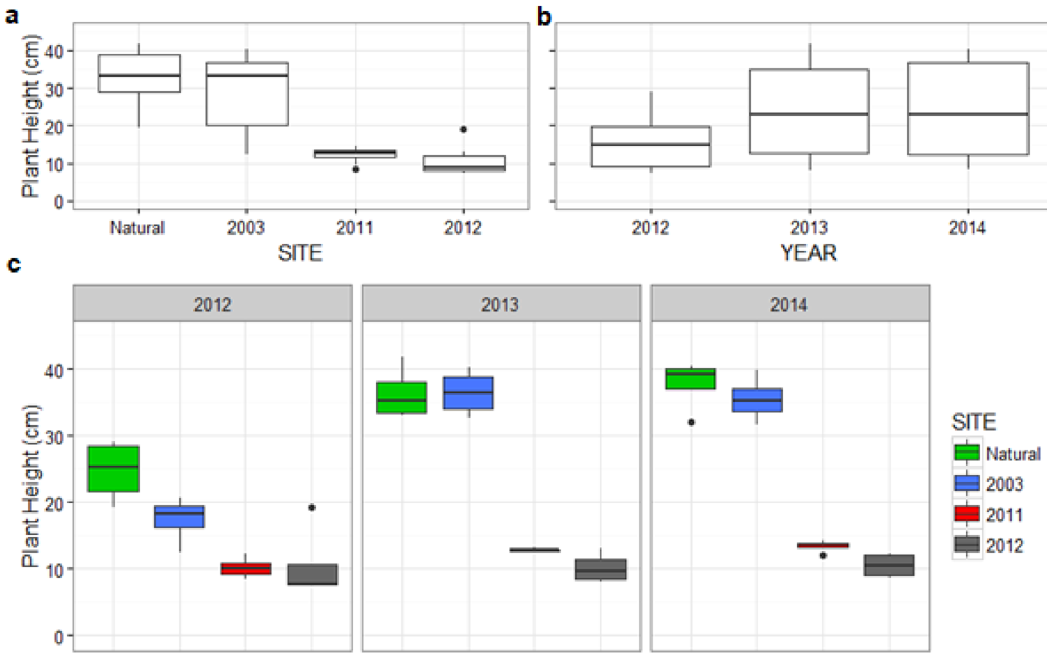


Figure 3.4: Boxplots of plant height (cm) for a) all sites; b) all years; and c): all sites and years sampled within the Eden estuary.

3.4.1.3. Plant Height – Seasonal Time Series

A GAM model with a gamma inverse link function was used to model the plant height relationship with site and date from November 2011 to March 2013. The interaction between site and year was found to be significant, the model with interaction reducing the AIC and improving the deviance explained. Smoother terms for sites were found to contribute significantly to the model (Figure 3.6, $p < 0.001$) and the model explained 85.0 % of deviance with an adjusted r^2 of 0.813.

Significant differences were found between sites ($F_{3, 136} = 85.76$, $p < 0.001$). The natural site which had the tallest plants (32.7 cm) was not significantly different from the oldest planted site, 2003 ($t = 1.73$, $p = 0.086$), which had the second tallest plants (29.8 cm). The two younger planted sites, 2011 and 2012, had significantly lower plant heights (13.2 cm and 11.2 cm respectively) than the natural site ($t = 14.71$, $p < 0.0001$ and $t = 6.64$, $p < 0.0001$ respectively).

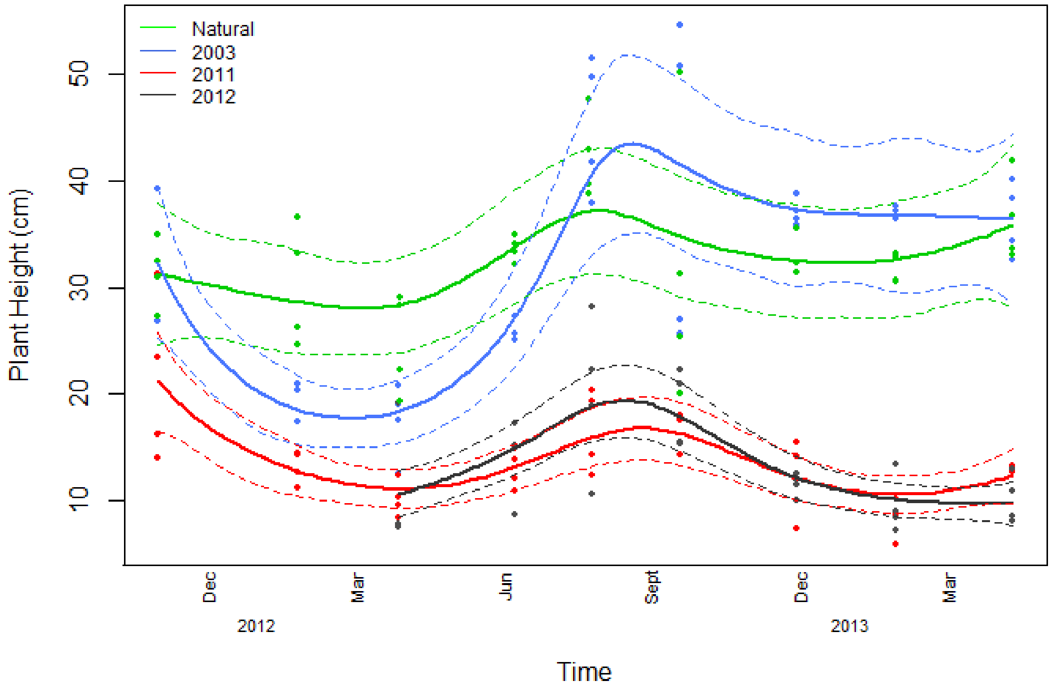


Figure 3.6: Changes in plant height over time for sites in the Eden estuary, plotted using a Gamma Generalised Additive Model with inverse link function. Points represent data. Solid lines represent model plot. Dashed lines represent confidence intervals (2 x standard error).

3.4.1.4. Plant Density – Three-Year Time Series

No significant differences were found for site*year interaction ($F_{6,36} = 0.468$, $p = 0.840$) or for plant density among years ($F_{2,36} = 2.84$, $p = 0.129$).

Significant differences in plant density among sites were found ($F_{3,36} = 69.30$, $p < 0.001$). *Post hoc* Tukey's test confirmed that the oldest planted site, 2003, was marginally significantly different from the natural site ($p = 0.0013$) and significantly different from the younger planted sites, 2011 and 2012. The younger planted sites were also significantly different from the natural site but were not significantly different from one another. The highest density was found at the natural site, followed by the 2003 site, and finally the 2011 and 2012 sites (Table 3.3).

Table 3.3: Summary statistics for plant density expressed in plants / m^2: mean and standard deviation for all sites and years sampled within the Eden estuary.

Site	Year			
	2012	**2013**	**2014**	**All Years**
Natural	934 ± 192	878 ± 199	1027 ± 205	946 ± 191
2003	593 191	691 265	778 ± 216	687 ± 219
2011	236 148	196 117	237 ± 80	223 ± 109
2012	46 ± 29	157 ± 55	135 ± 46	113 ± 64
All Sites	452 ± 378	481 ± 359	544 ± 407	492 ± 376

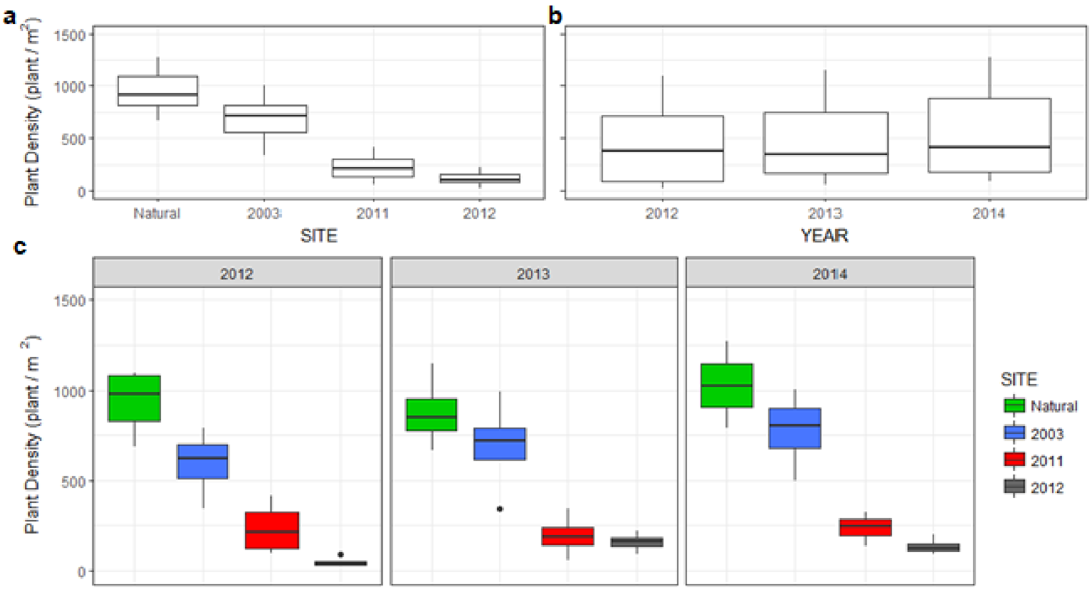


Figure 3.7: Boxplots of plant density (plants.m^{-2}) for a) all sites; b) all years and c) all sites and years sampled within the Eden estuary.

3.4.1.5. Plant Density – Seasonal time series

A GAM model with a gamma inverse link function was used to model the plant density relationship with site and date from November 2011 to March 2013. The interaction between site and year was found to be significant, the model with interaction reducing the AIC and improving the explained deviance. Smoother terms for sites were found to contribute significantly to the model (Figure 3.8, $p < 0.05$) and the model explained 85.8% of deviance with an adjusted r^2 of 0.827.

Significant differences were found between sites ($F_{3, 136} = 66.60$, $p < 0.001$). The natural site which had the highest density (725 plant / m^2) was significantly different from site 2003 ($t = 3.21$, $p < 0.001$, 552 plant / m^2), site 2011 ($t = 13.03$, $p < 0.0001$, 149 m^{-2}) and site 2012 ($t = 5.335$, $p < 0.0001$, 61 plant / m^2). The younger sites, 2011 and 2012, had a notably lower plant density than the oldest planted site, 2003. It was not possible to test the significance of this using this model.

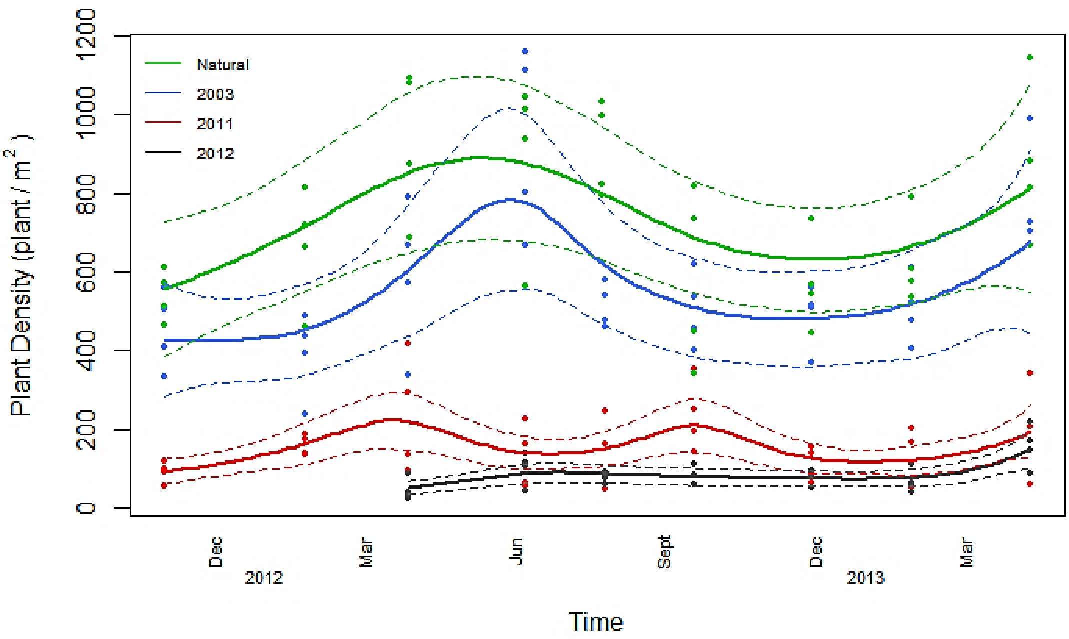


Figure 3.8: Changes in plant density over time for sites in the Eden estuary. Plotted using a Gamma Generalised Additive Model with inverse link function. Points represent data. Solid lines represent model plot. Dashed lines represent confidence intervals (2 x standard error).

3.4.2. Sediment Stability

3.4.2.1. Correlations

Erosion threshold and shear strength had a significant weak negative correlation ($r_s = -0.12$, $p < 0.05$, Figure 3.9).

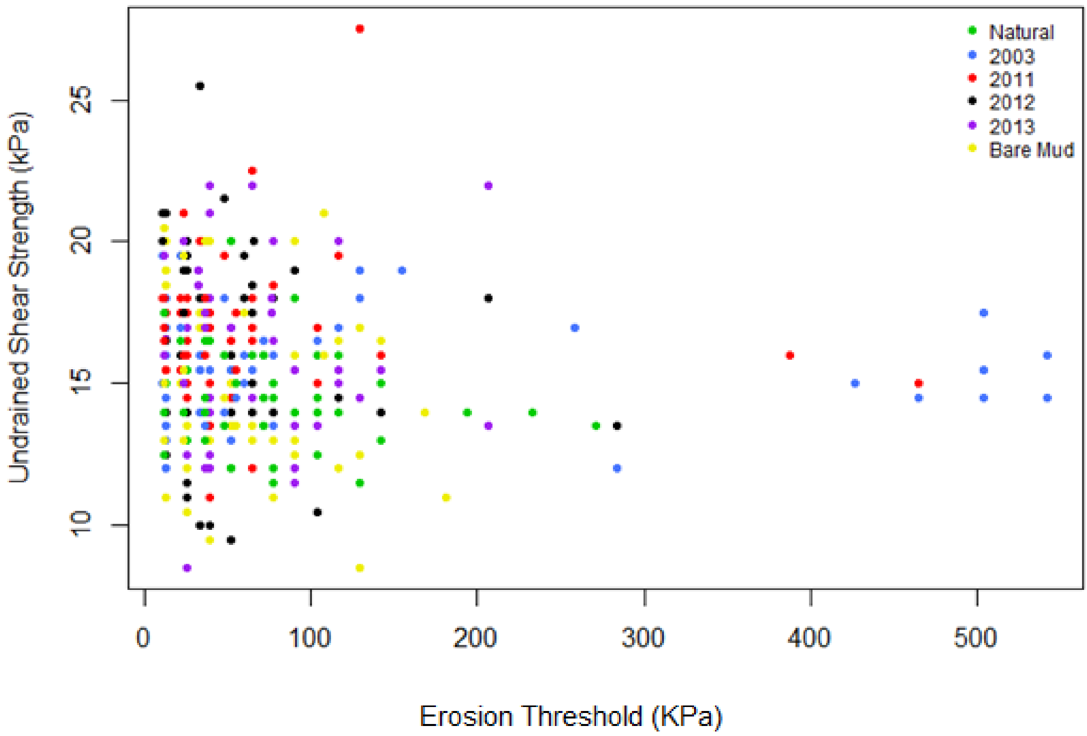


Figure 3.9: Realtionship between sediment stability measures: erosion threshold and shear strength for all study sites at all time points.

3.4.2.2. Erosion threshold – Three-Year Time Series

A significant difference was found for erosion threshold among years ($H_2 = 8.42$, $p < 0.05$) and among sites ($H_5 = 27.66$, $p < 0.001$) (Figure 3.10, Table 3.4). *Post hoc* Dunn's test confirmed that sediment stability was enhanced in the year 2012 and declined in years 2013 and 2014 which did not differ significantly from one another. The higher sediment stability observed in the year 2012 is likely due to the oldest planted site and the natural site being more stable in this year. The natural and oldest planted sites (2003) which had the highest sediment stability were significantly different from the bare mud site which was the least stable of the sites. The oldest planted site (2003) was also significantly more stable than the youngest planted site (2013).

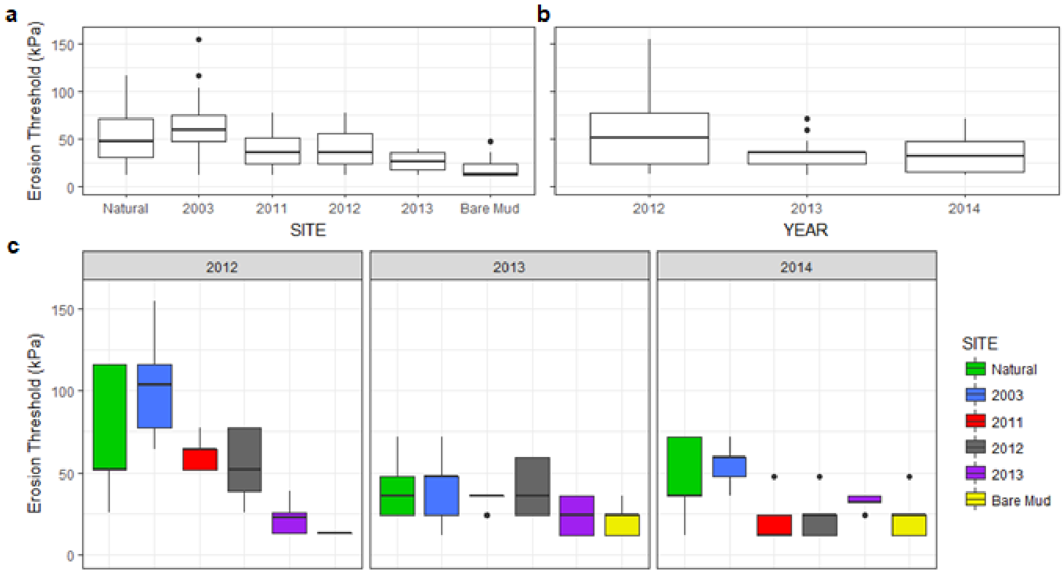


Figure 3.10: Boxplots of erosion threshold (erosion threshold, kPa) of surface sediment for a) all sites; b) all years and c) all sites and years sampled within the Eden estuary.

Table 3.4: Summary statistics for erosion threshold (erosion threshold, kPa) of surface sediment: mean and standard deviation for all sites and years sampled within the Eden estuary.

Erosion Threshold (kPa)	YEAR			
SITE	**2012**	**2013**	**2014**	**All Years**
Natural	72.3	40.6	45.3	52.7
	41.4	20.0	25.9	31.7
2003	103.3	40.6	54.9	66.3
	35.4	23.3	13.6	36.6
2011	62.0	33.4	21.5	39.0
	10.8	5.3	15.6	20.5
2012	54.2	40.6	23.9	39.6
	23.1	18.1	14.6	21.7
2013	22.6	23.9	31.8	26.1
	10.7	11.9	4.9	9.9
Bare Mud	12.9	21.5	23.9	19.4
	0.0	10.0	14.6	10.6
All Sites	54.6	33.4	33.5	40.5
	38.3	16.7	19.3	28.1

3.4.2.3. Erosion Threshold – Seasonal Time Series

A GAM model with a gamma inverse link function was used to model the surface sediment erosion threshold with site and time between December 2012 and March 2013. The interaction between site and time was found to be significant, with the model interaction term reducing the AIC and improving the deviance explained. Smoother terms for all sites over time were found to contribute significantly to the model (Figure 3.11, $p < 0.05$) and the model explained 47.3% of the deviance with an adjusted r^2 of 0.468. There were no significant differences found between sites ($F_{5, 481} = 1.87$, $p > 0.10$).

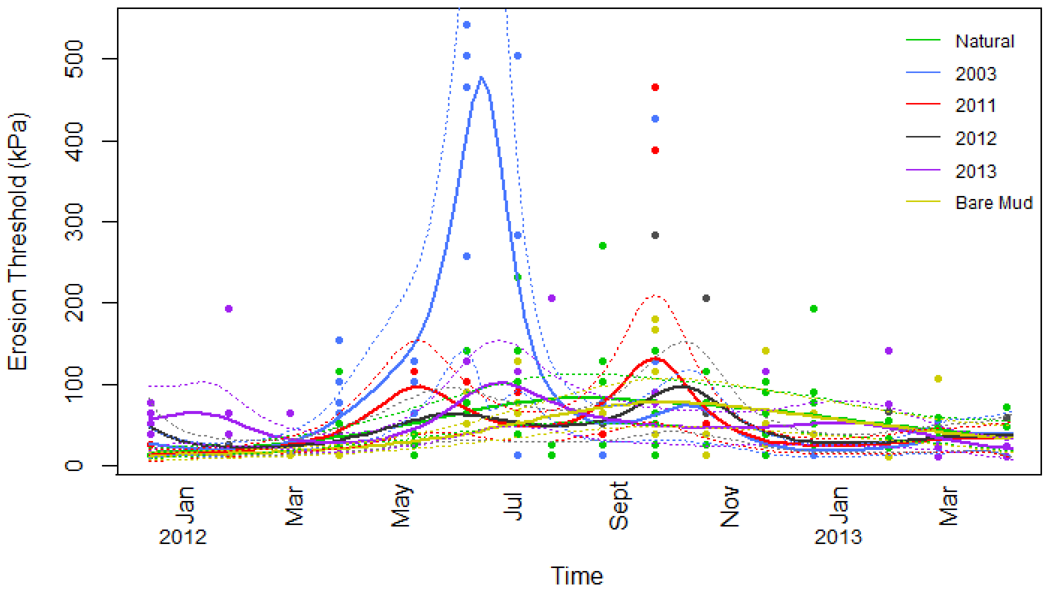


Figure 3.11: Changes in surface sediment erosion threshold (kPa) over time for sites in the Eden estuary. Plotted using a Gamma Generalised Additive Model with inverse link function. Points represent data. Solid lines represent model plot. Dashed lines represent confidence intervals (2 x standard error).

3.4.2.4. Undrained Shear Strength – Three-Year Time Series

A significant interaction between site and year was found for undrained shear strength ($F_{10,72} = 3.97$, $p > 0.01$; Figure 3.12, Table 3.5). A *post hoc* Tukey test revealed that the three youngest planted sites (2011, 2012 and 2013) had a significantly higher shear strength than the natural and oldest planted site (2003), except for site 2013 prior to its planting (year 2012). The shear strength at the bare mud site was notably higher in year 2012 than in years 2013 and 2014. The bare mud site generally differed significantly from the two youngest planted sites, 2012 and 2013.

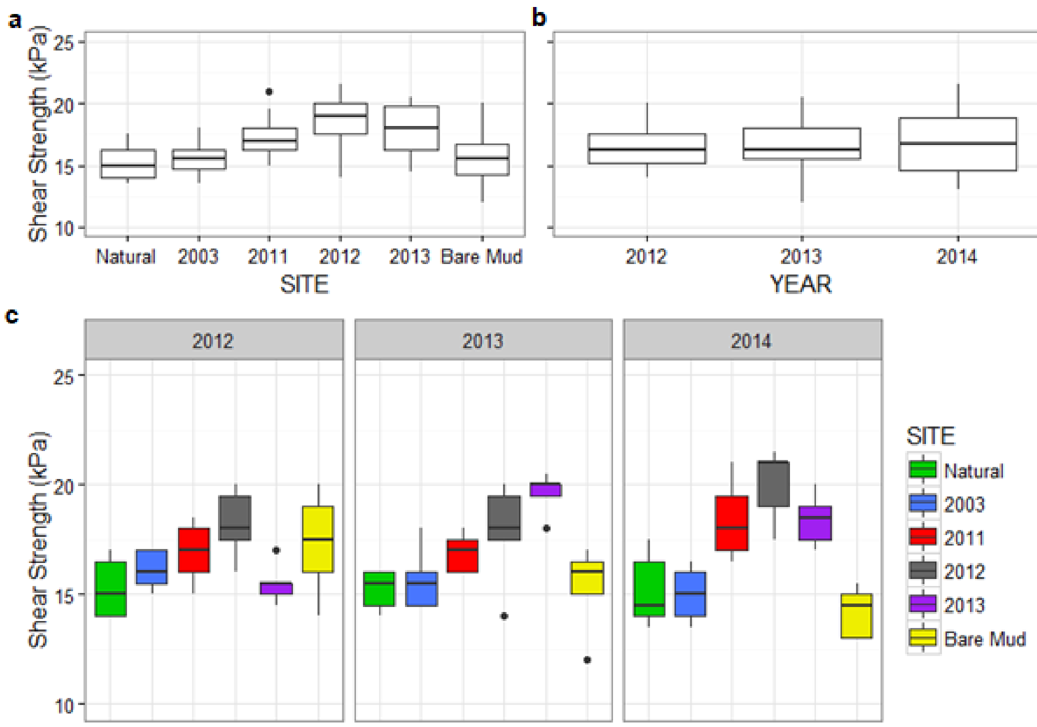


Figure 3.12: Boxplots of erosion threshold (kPa) of surface sediment for a) all sites; b) all years and c) all sites and years sampled within the Eden estuary.

Table 3.5: Summary statistics for erosion threshold (erosion threshold, kPa) of surface sediment: mean and standard deviation for all sites and years sampled within the Eden estuary.

Undrained Shear Strength (kPa)	YEAR			
SITE	2012	2013	2014	All Years
Natural	15.3	15.2	15.2	15.2
	1.4	0.9	1.7	1.3
2003	16.1	15.7	15.0	15.6
	0.9	1.4	1.3	1.2
2011	16.9	16.9	18.4	17.4
	1.4	0.9	1.9	1.5
2012	18.2	17.8	20.0	18.7
	1.6	2.4	1.7	2.0
2013	15.5	19.6	18.4	17.8
	0.9	1.0	1.2	2.0
Bare Mud	17.3	15.3	14.2	15.6
	2.4	2.0	1.2	2.2
All Sites	16.6	16.8	16.9	16.7
	1.7	2.1	2.6	2.2

3.4.2.5. Undrained Shear Strength – Seasonal Time Series

A GAM model with a gamma inverse link function was used to model the surface sediment erosion threshold with site and time from March 2012 and March 2013. The interaction between site and time was found to be significant, with the model with interaction reducing the AIC and improving the deviance explained. Smoother terms for sites over time were found to contribute significantly to the model (Figure 3.14, $p < 0.05$) and the model explained 37.8 % of the deviance with an adjusted r^2 of 0.319.

Significant differences were found between sites ($F_{5, 390} = 6.94$, $p < 0.001$). The bare mud and natural sites, which had the lowest shear strength of all the sites (14.8 kPa and 14.5 kPa respectively), were not significantly different from one another ($t = 0.71$, $p > 0.1$). All the planted sites had significantly higher shear stress values compared to the natural site. Site 2011 had the highest shear strength (16.3 kPa, $t = 4.87$, $p < 0.001$), followed by site 2013 (15.9 kPa, $t = 3.76$, $p < 0.001$), closely followed by site 2012 (15.8 kPa, $t = 3.38$, $p < 0.001$), with the oldest site (2003) having the lowest shear stress of the planted sites (15.4 kPa, $t = 2.30$, $p < 0.05$). The bare mud had significantly lower sheer stress value compared to the three younger planted sites (site 2011 ($t = 4.13$, $p < 0.001$), site 2012 ($t = 2.66$, $p < 0.001$) and site 2013 ($t = 2.82$, $p < 0.01$)) but did not differ significantly from the oldest planted site (2003).

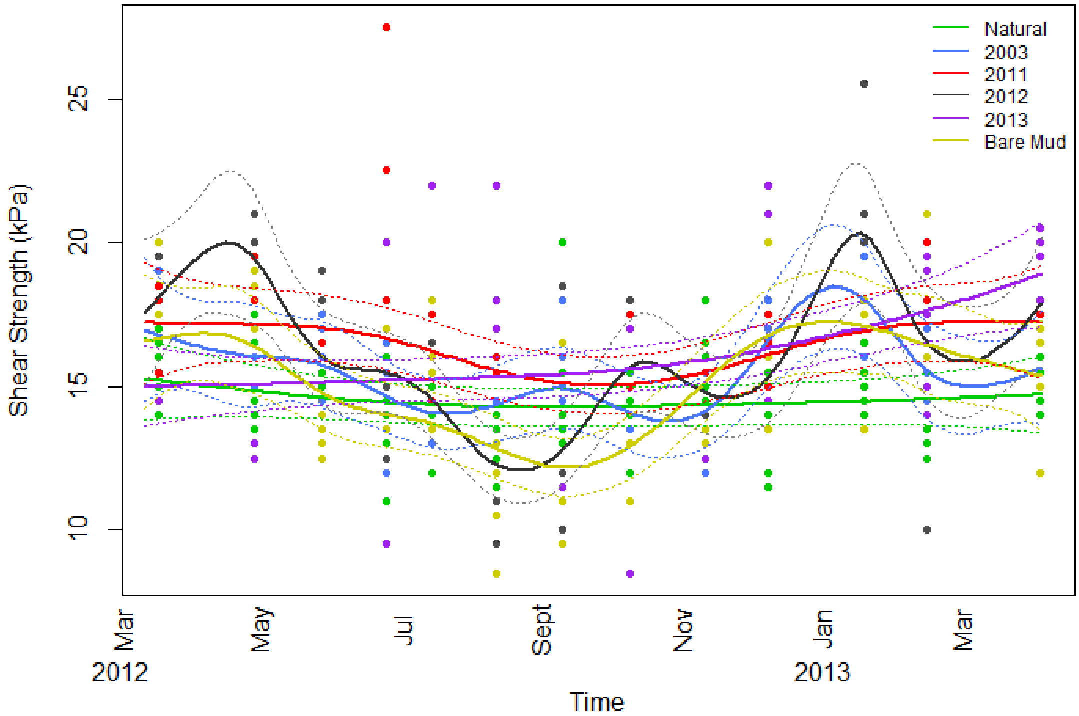


Figure 3.14: Changes in undrained shear strength of the top 5 cm of sediment over time for sites in the Eden estuary. Plotted using a Gamma Generalised Additive Model with inverse link function. Points represent data. Solid lines represent model plot. Dashed lines represent confidence intervals (2 x standard error).

3.4.2.6. Wet Bulk Density - Three-Year Time Series

A significant interaction between site and year was found for bulk density ($F_{10,54} = 2.63$, $p < 0.01$; Figure 3.15, Table 3.6). A *post hoc* Tukey test did not reveal any significant trends in the data and high variability was found (Figure 3.15.)

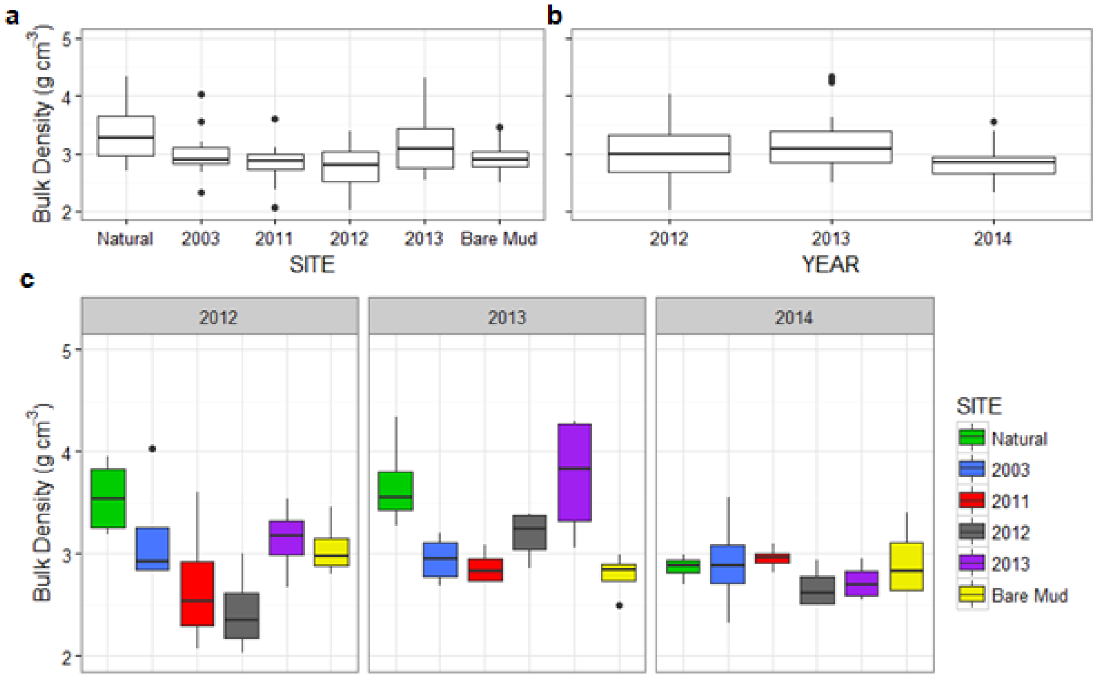


Figure 3.15: Boxplots of surface bulk density (g cm^{-3}) for a) all sites; b) all years and c) all sites and years sampled within the Eden estuary.

Table 3.6: Summary statistics for surface bulk density (g cm^{-3}): mean and standard deviation for all sites and years sampled within the Eden estuary.

Bulk Density (g cm^{-3})	YEAR			
SITE	**2012**	**2013**	**2014**	**All Years**
Natural	3.55 ± 0.37	3.68 ± 0.46	2.87 ± 0.13	3.02 ± 0.49
2003	3.18 ± 0.57	2.94 ± 0.24	2.91 ± 0.51	3.01 ± 0.44
2011	2.69 ± 0.66	2.86 ± 0.17	2.96 ± 0.12	2.84 ± 0.38
2012	2.44 ± 0.42	3.18 ± 0.25	2.67 ± 0.20	2.76 ± 0.43
2013	3.14 ± 0.36	3.75 ± 0.62	2.72 ± 0.18	3.20 ± 0.59
Bare Mud	3.05 ± 0.29	2.79 ± 0.21	2.92 ± 0.36	2.92 ± 0.29
All Sites	3.01 ± 0.55	3.20 ± 0.51	2.84 ± 0.28	3.02 ± 0.48

3.4.2.7. Wet Bulk Density – Seasonal Time Series

A GAM model with a gamma inverse link function was used to model the surface sediment bulk density relationship with site and season from March 2012 to March 2013. The interaction between site and season was not significant, with the model incorporating interaction having a higher AIC and no improvement in the deviance explained. The model explained 41.7 % of the deviance with an adjusted r^2 of 0.415. The smoother term for the differences between seasons for all sites combined was found to contribute significantly to the model (Figure 3.16, $F_{2.97,\ 288} = 63.33$, $p < 0.0001$). The natural and the bare mud sites did not differ significantly from any of the planted sites or one another ($p < 0.05$).

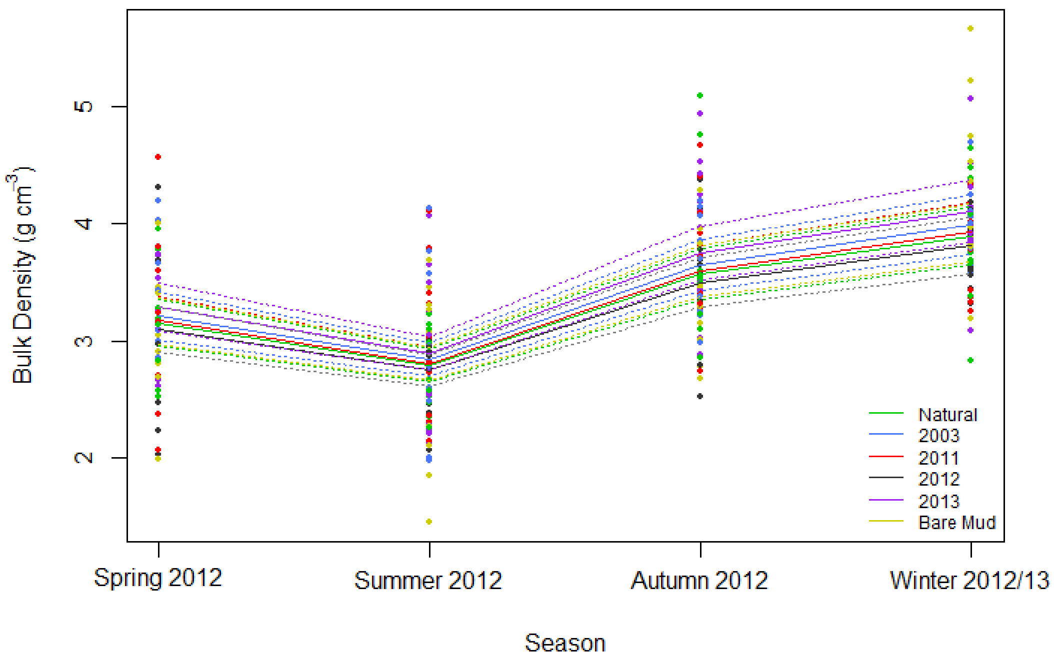


Figure 3.16: Changes in surface sediment wet bulk density over seasons for sites in the Eden estuary. Plotted using a Gamma Generalised Additive Model with inverse link function. Points represent data. Solid lines represent model plot. Dashed lines represent confidence intervals (2 x standard error).

3.4.3. Surface Sediment Characteristics

3.4.3.1. Correlations

Spearman's rank correlations were carried out for all surface sediment characteristics except water where the data was not normally distributed. All surface sediment characteristics were found to be significantly correlated with one another ($p < 0.001$) (Figure 3.17).

Water content had a moderately positive correlation with organic content and mud content. Organic content and mud content also had a moderately strong positive correlation with one another. D_{50} had negative correlations with all sediment characteristics; a strong correlation was found with mud content, moderate with organic content and weak with water content.

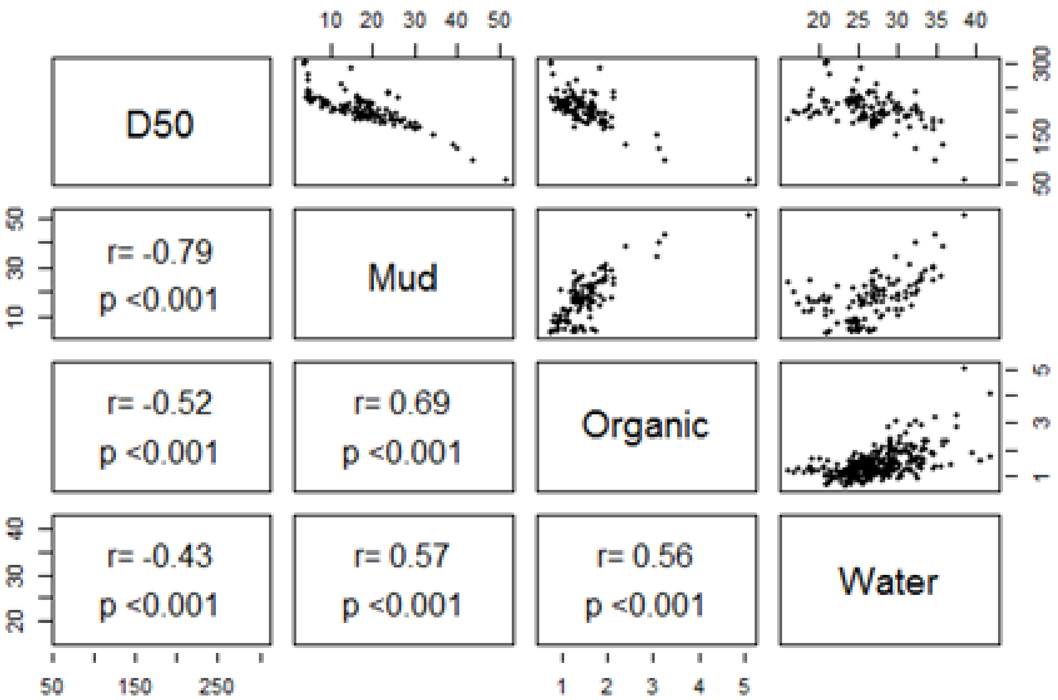


Figure 3.17: Scatter plot (upper panel) and Spearman's rank correlations with associated statistical significance (lower panel) between surface sediment characteristics: median grain size, D_{50} (µm), mud content (%), organic content (%) and water content (%).

3.4.3.2. Sediment Texture – Three-Year Time Series

In years 2012 and 2014, the sediment texture groups for each site were similar, with the natural, bare mud and 2003 sites all having muddy-sand texture and the 2011, 2012 and 2013 sites having a coarser sandy texture. In year 2013, the sediment texture groups differed for all sites except bare mud and 2003 as compared to the other years. The natural site was found to have a coarser sand texture whilst the 2011 and 2012 sites became finer with a muddy sand texture. The 2013 site also became finer with both sand and muddy sand being found at the site.

Table 3.7: Sediment Texture Type for all sites over three-year sampling period. MS: muddy sand, S: sand.

Site	Year		
	2012	2013	2014
Natural	MS	S	MS
Bare Mud	MS	MS	MS
2003	MS	MS	MS
2011	S	MS	S
2012	S	MS	S
2013	S	S/MS	S

Water content was found to be significantly different for different sediment texture groups (H_1 = 39.623, $p < 0.001$) with muddy sandy sediment having a higher water content than sandy sediment (29.0 % ± 3.07, 24.24 % ± 1.61, respectively).

Organic content was found to be significantly different for different sediment texture groups (H_1 = 31.887, $p < 0.001$) with muddy sandy sediment having a higher organic content than sandy sediment (1.55 % ± 0.33, 1.04 % ± 0.24, respectively).

D_{50} and mud content were found to be significantly different for different sediment texture groups (H_1 = 34.772, $p < 0.001$ and H_1 = 52.235, $p < 0.001$, respectively) with muddy sandy sediment having a smaller D_{50} and higher mud content than sandy sediment (198.6 mm ± 22.4, 233.2 mm ± 26.2 and 20.15 % ± 5.0, 6.28 % ± 2.0, respectively).

Chlorophyll *a* concentration was found to be significantly different for different sediment texture groups ($H_1 = 22.436$, $p < 0.001$) with muddy sandy sediment having a higher concentration than sandy sediment (209.7 ± 79.0, 133.6 ± 41.7, respectively).

There was no significant difference in colloidal carbohydrate concentration ($H_1 = 0.538$, $p = 0.463$) or protein concentration ($H_1 = 0.573$, $p = 0.449$) for sediment texture groups.

There was no significant difference in bulk density for sediment texture groups ($H_1 = 1.00$, $p = 0.32$).

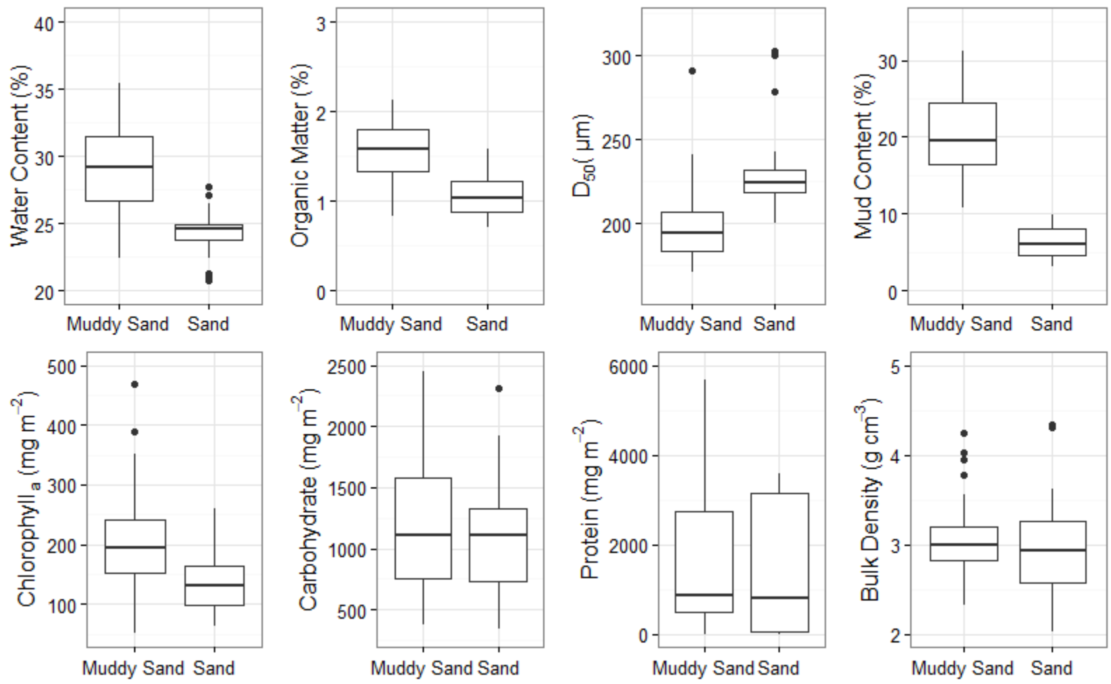


Figure 3.18: Boxplots for variables between sediemnt texture groups at all sites.

3.4.3.3. D_{50} – Three-Year Time Series

A significant interaction was found between site and year for D_{50} ($F_{10, 54} = 22.66$, $p < 0.001$). The natural and bare mud sites showed the opposite pattern of change in D_{50} between years compared to the planted sites. The natural site, and to a lesser extent, the bare mud site increased in D_{50} from 2012 to 2013 and then decreased from 2013 to 2014. The younger planted sites (2013, 2012, 2011) and to a lesser extent the oldest planted site (2003) decreased D_{50} from 2012 to 2013 and increased from 2013 to 2014 (Figure 3.19, Table 3.8). Trends in differences between individual sites were less obvious with *post hoc* Tukey test identifying that the oldest planted site had a significantly smaller D_{50} than all sites except for the bare mud and that the natural site had significantly larger D_{50} than all sites except for site 2013.

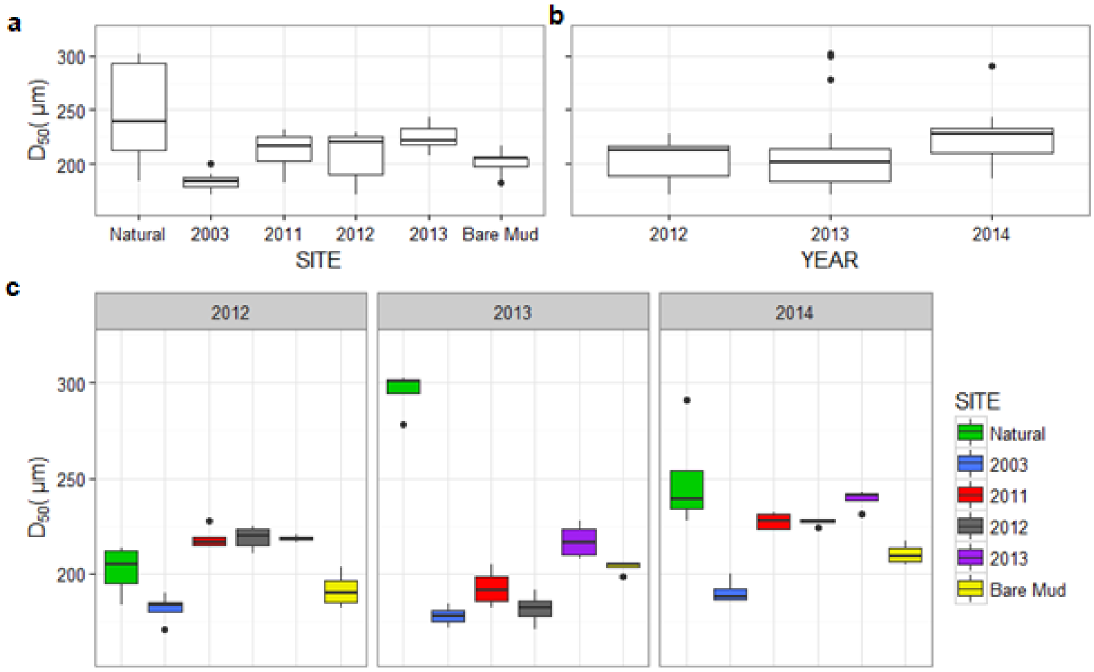


Figure 3.19: Boxplots of surface sediment median grain size, D_{50} (µm) for top a) all sites; b) all years and c) all years and bottom: all sites and years sampled within the Eden estuary.

Table 3.8: Summary statistics for surface sediment median grain size, D_{50} (µm): mean and standard deviation for all sites and years sampled within the Eden estuary.

D_{50} (µm)	YEAR			
SITE	**2012**	**2013**	**2014**	**All Years**
Natural	201.8 ± 13.8	295.5 ± 11.5	249.0 ± 28.4	248.8 ± 43.6
2003	181.9 ± 8.1	178.0 ± 5.3	190.4 ± 6.8	183.4 ± 8.2
2011	218.4 ± 6.1	192.6 ± 10.1	227.4 ± 4.6	212.8 ± 16.7
2012	218.7 ± 6.5	181.6 ± 8.7	227.1 ± 2.1	209.1 ± 21.4
2013	218.6 ± 1.8	217.3 ± 9.3	239.1 ± 5.5	225.0 ± 11.9
Bare Mud	191.5 ± 9.7	203.5 ± 3.5	210.2 ± 5.4	201.7 ± 10.1
All Sites	205.1 ± 16.7	211.4 ± 41.4	223.9 ± 22.4	213.5 ± 29.5

3.4.3.4. Mud Content – Three-Year Time Series

It was not possible to test for a significant interaction due to the mud content data violating the assumptions for homogeneity and normality. However, it should be noted that a similar pattern to that observed in the D_{50} data was observed. The bare mud and natural sites both declined in mud content from 2012 to 2013 and then increasing again from 2013 and 2014. All planted sites, but only marginally for the oldest site (2003), increased in mud content from 2012 to 2013 and then decreased from 2013 to 2014 (Figure 3.20, Table 3.9).

No significant differences were found among years for mud content ($H_2 = 3.84$, $p > 0.1$); a significant difference was found for mud content among sites ($H_5 = 18.49$, $p < 0.01$).

Post hoc Dunn's test confirmed that the oldest planted site (2003) and the bare mud site which had two highest mud contents were both significantly different from the youngest planted site (2013) which had the lowest mud content. No other significant differences in the sites were found.

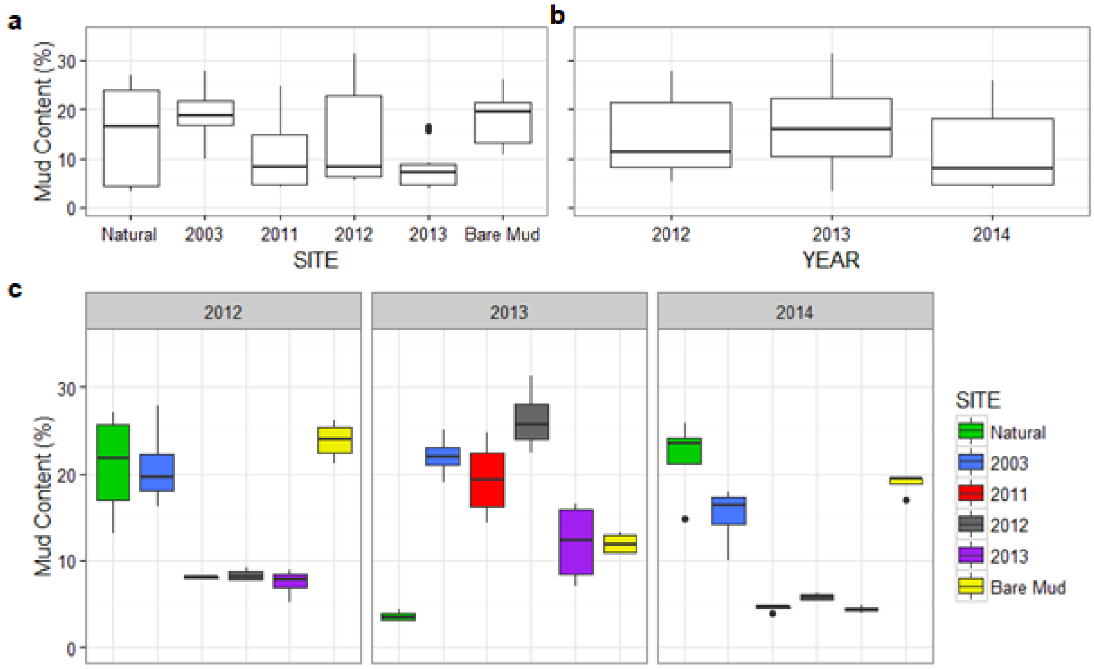


Figure 3.20: Boxplots of surface sediment mud content (%) for a) all sites; b) all years and c) all sites and years sampled within the Eden estuary.

Table 3.9: Summary statistics for surface sediment mud content (%): mean and standard deviation for all sites and years sampled within the Eden estuary.

Mud Content (%)	**YEAR**			
SITE	**2012**	**2013**	**2014**	**All Years**
Natural	20.9 ± 6.5	3.6 ± 0.6	21.9 ± 4.9	15.5 ± 9.7
2003	20.8 ± 5.1	22.0 ± 2.5	15.1 ± 3.6	19.3 ± 4.7
2011	8.1 ± 0.1	19.4 ± 4.7	4.5 ± 0.4	10.7 ± 7.1
2012	8.3 ± 0.7	26.3 ± 3.8	5.8 ± 0.4	13.5 ± 9.7
2013	7.4 ± 1.6	12.0 ± 4.7	4.4 ± 0.4	7.9 ± 4.2
Bare Mud	23.8 ± 2.3	12.0 ± 1.3	18.8 ± 1.3	18.2 ± 5.3
All Sites	14.9 ± 7.8	15.9 ± 8.2	11.8 ± 7.6	14.2 ± 8.0

3.4.3.5. Organic Content – Three-Year Time Series

A significant interaction was found between site and year for organic content ($F_{10,54}$ = 19.05, $p < 0.001$; Figure 3.21, Table 10). The bare mud and natural sites all declined in organic content from 2012 to 2013 and then increasing again from 2013 and 2014. Conversely, the younger planted sites (2011, 2012 and to a lesser extent 2013), increased in organic content from 2012 to 2013 and then decreased from 2013 to 2014. The oldest planted site (2003) increased slightly throughout the measured years (Figure 3.21, Table 3.10). A *post hoc* Tukey test indicated that within any individual year, the organic content at the natural site differed significantly from all other sites. The bare mud site was generally significantly different from the three youngest planted sites but not the oldest. The oldest planted site was also found to be significantly different from all three younger planted sites in years 2012 and 2014.

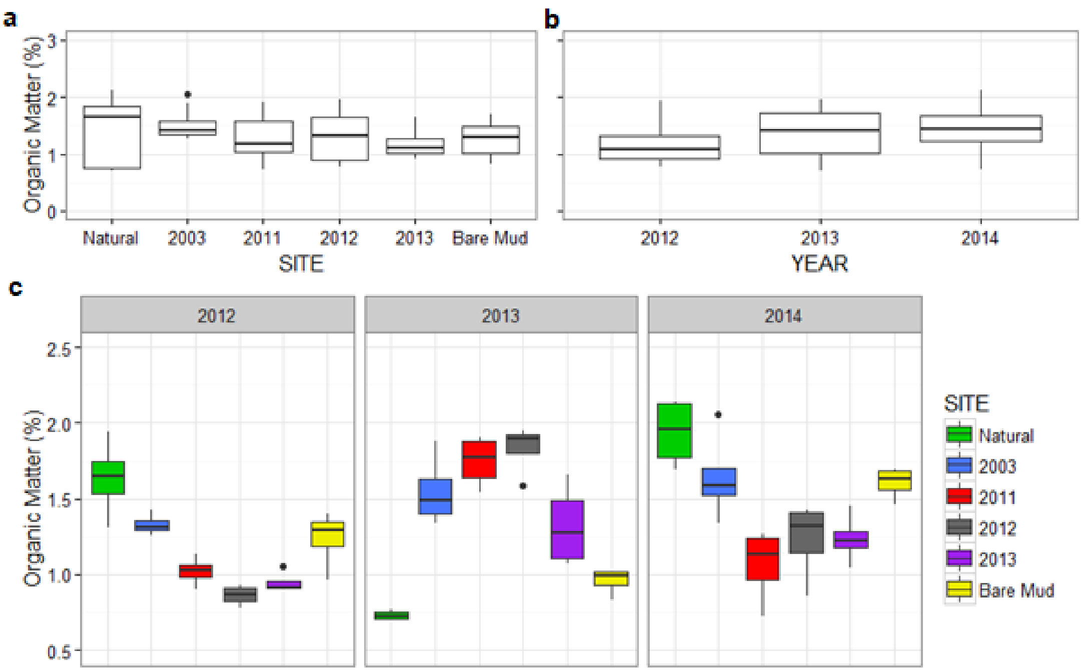


Figure 3.21: Boxplots of surface sediment organic matter content (%) for a) all sites; b) all years and c) all sites and years sampled within the Eden estuary.

Table 3.10: Summary statistics for surface sediment organic matter content (%): mean and standard deviation for all sites and years sampled within the Eden estuary.

Organic Content (%)	YEAR			
SITE	2012	2013	2014	All Years
Natural	1.63 ± 0.26	0.73 ± 0.03	1.94 ± 0.23	1.44 ± 0.56
2003	1.33 ± 0.08	1.55 ± 0.24	1.64 ± 0.30	1.51 ± 0.25
2011	1.02 ± 0.10	1.75 ± 0.17	1.07 ± 0.25	1.28 ± 0.38
2012	0.86 ± 0.07	1.83 ± 0.16	1.23 ± 0.26	1.31 ± 0.45
2013	0.94 ± 0.07	1.32 ± 0.28	1.24 ± 0.16	1.17 ± 0.24
Bare Mud	1.24 ± 0.19	0.96 ± 0.09	1.60 ± 0.11	1.27 ± 0.30
All Sites	1.17 ± 0.30	1.36 ± 0.44	1.45 ± 0.37	1.33 ± 0.39

3.4.3.6. Organic Content – Seasonal Time Series

A GAM model with a gamma inverse link function was used to model the surface sediment organic content relationship with site and season from March 2012 to March 2013. The interaction between site and season was found to be significant, with the model with interaction reducing the AIC and improving the deviance explained. Smoother terms accounting for the differences between seasons for sites were found to contribute significantly to the model (Figure 3.22, $p < 0.01$) and the model explained 54 % of deviance with an adjusted r^2 of 0.490.

Significant differences were found between sites ($F_{5, 288} = 32.54$, $p < 0.001$). The natural site, which had the fourth highest organic content (1.30%) was significantly different from site 2003 which had the highest organic content of all sites (1.97%, $t = 8.17$, $p < 0.001$) and site 2013 which had the lowest organic content (1.14 %, $t = 2.64$, $p < 0.01$). The natural site did not differ significantly from any other sites, including the bare mud site. The bare mud site which had the second highest organic content (1.43 %) differed significantly from site 2003 (t = 6.39, $p < 0.001$) and sites 2012 and 2013 which had the two lowest organic contents (1.28 %, t = 2.17, $p < 0.05$ and 1.14, t = 4.53, $p < 0.001$, respectively).

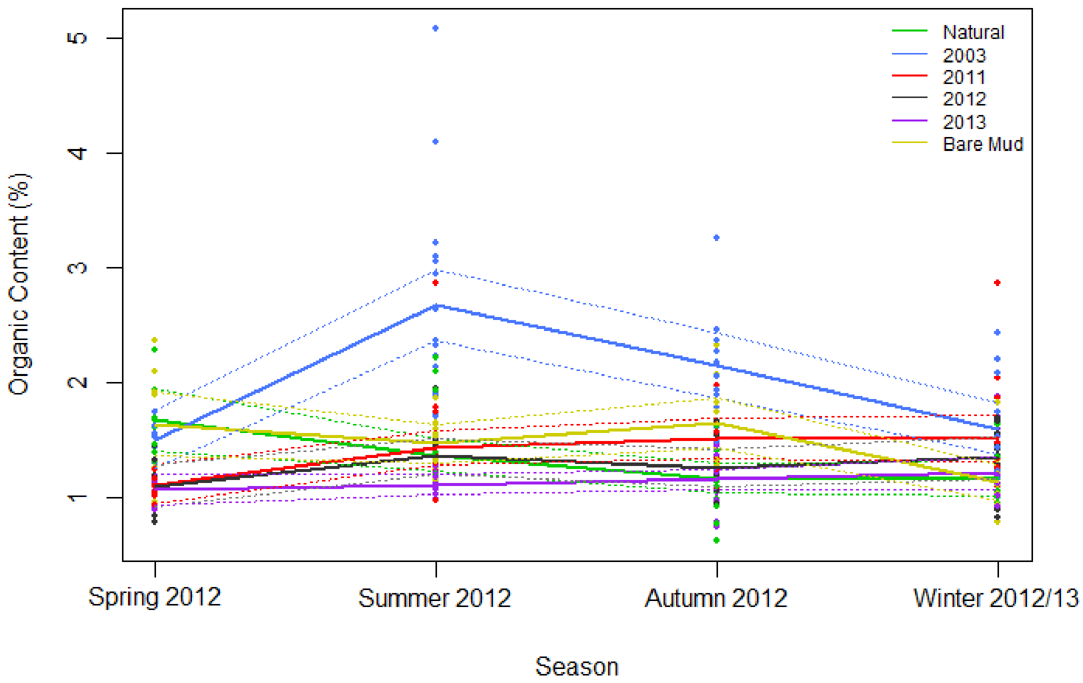


Figure 3.22: Changes in surface sediment water content over seasons for sites in the Eden estuary. Plotted using a Gamma Generalised Additive Model with inverse link function. Points represent data. Solid lines represent model plot. Dashed lines represent confidence intervals (2 x standard error).

3.4.3.7. Water Content – Three-Year Time Series

A significant interaction was found between site and year ($F_{10,54} = 16.47$, $p < 0.001$; Figure 3.23, Table 3.11). The bare mud and natural sites all declined in water content from 2012 to 2013 and then increasing again from 2013 to 2014. Conversely, the 2011 and 2012 sites increased in water content from 2012 to 2013 and then decreased from 2013 to 2014. The youngest (2013) and the oldest (2003) planted sites both remained fairly constant throughout the years. A *post hoc* Tukey test confirmed that water content at the bare mud site was significantly higher than at all other sites in years 2012 and 2014. The natural site was significantly different from all the planted sites in years 2012 and 2013, and significantly different from the three youngest planted sites in 2014.

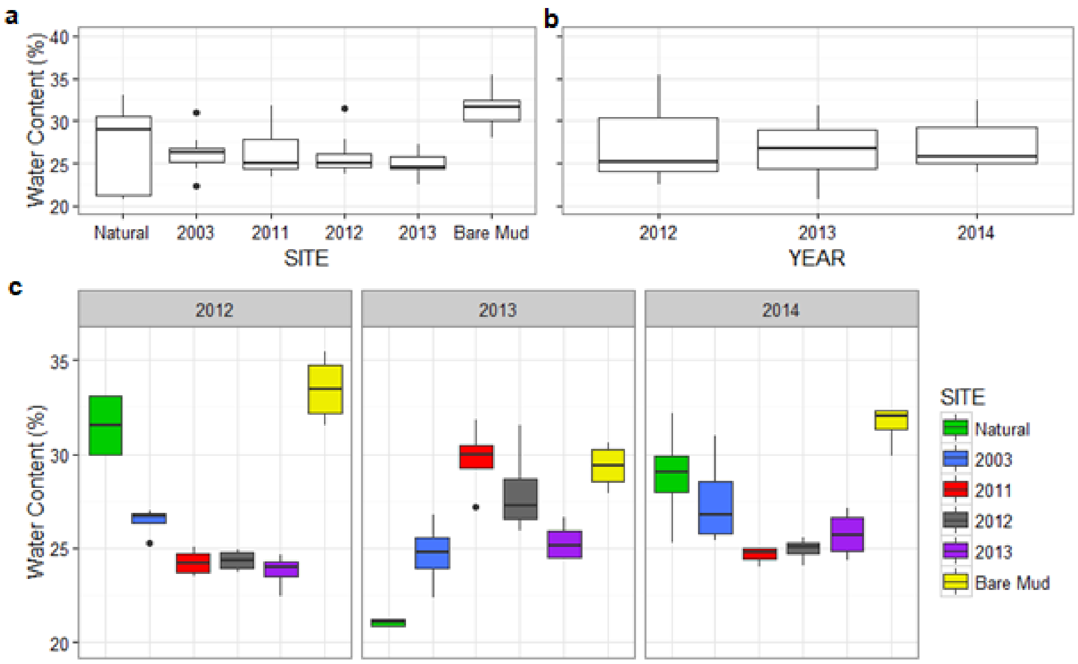


Figure 3.23: Boxplots of surface sediment water content (%) for a) all sites; b) all years and c) all sites and years sampled within the Eden estuary.

Table 3.11: Summary statistics for surface sediment water content (%): mean and standard deviation for all sites and years sampled within the Eden estuary.

Water Content (%)	**YEAR**			
SITE	**2012**	**2013**	**2014**	**All Years**
Natural	31.5 ± 1.8	21.0 ± 0.2	28.9 ± 2.8	27.1 ± 5.0
2003	26.4 ± 0.8	24.7 ± 1.8	27.5 ± 2.5	26.2 ± 2.1
2011	24.2 ± 0.7	29.7 ± 1.9	24.6 ± 0.5	26.2 ± 2.8
2012	24.3 ± 0.6	28.0 ± 2.5	28.1 ± 6.3	26.8 ± 4.0
2013	23.8 ± 0.9	25.3 ± 1.0	25.7 ± 1.3	24.9 ± 1.3
Bare Mud	33.5 ± 1.8	29.3 ± 1.2	31.6 ± 1.1	31.5 ± 2.2
All Sites	27.3 ± 4.0	26.4 ± 3.4	27.7 ± 3.6	27.1 ± 3.7

3.4.3.8. Water Content – Seasonal Time Series

A GAM model with a gamma inverse link function was used to model the surface sediment water content relationship with site and season from March 2012 to March 2013. The interaction between site and season was found to be significant, with the model with interaction reducing the AIC and improving the deviance explained. A weighted variance structure by season was incorporated into the model due to different seasons having different variances. The 'VarIdent' function was used which allows for each level of a factor to have a different variance (Pinheiro and Bates, 2000). Smoother terms accounting for the differences between seasons for sites were found to contribute significantly to the model (Figure 3.24, $p < 0.001$) and the model had an adjusted r^2 of 0.411.

Significant differences were found between sites ($F_{5, 288} = 18.96$, $p < 0.001$). The natural site which had the third highest water content (27.0%) was significantly different from all sites except for site 2011. It had a higher water content than the three youngest planted sites: site 2011 (26.4%, $t = 0.94$, $p > 0.05$), site 2012 (25.36%, $t = 2.45$, $p < 0.05$) and site 2013 (24.6%, $t = 4.03$, $p < 0.0001$). It had a lower water content than the oldest planted site, 2003 (30.2%, $t = 5.00$, $p < 0.0001$), and the bare mud site (28.5%, $t = 2.28$, $p < 0.05$). All sites were significantly different from the bare mud site ($p < 0.001$).

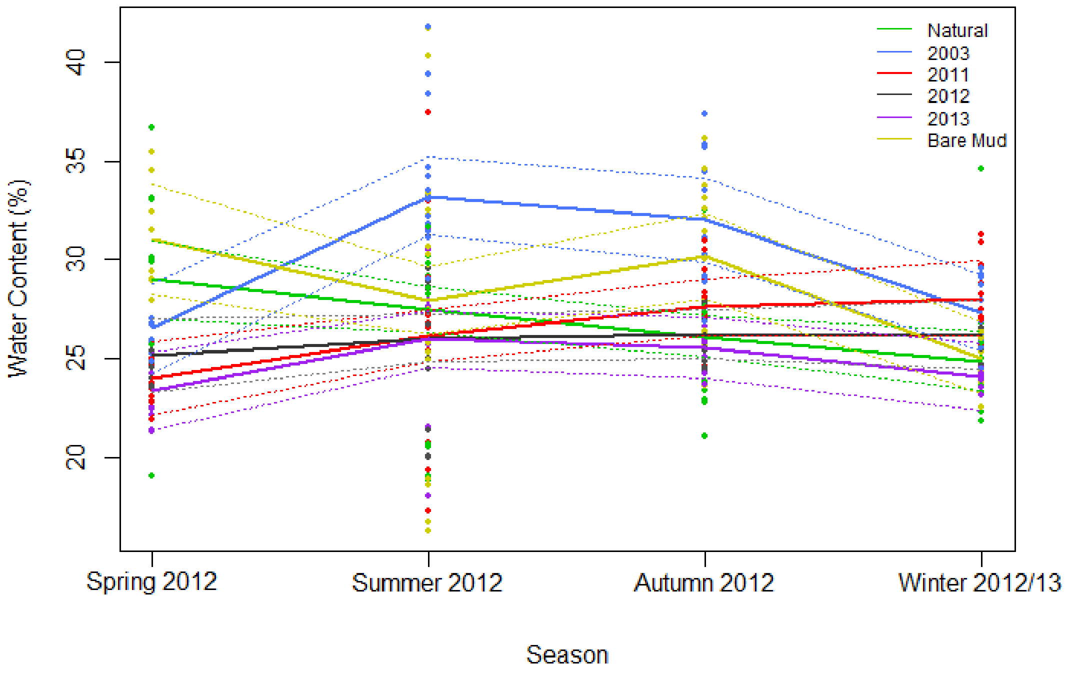


Figure 3.24: Changes in surface sediment water content over seasons for sites in the Eden estuary. Plotted using a Gamma Generalised Additive Model with inverse link function. Points represent data. Solid lines represent model plot. Dashed lines represent confidence intervals (2 x standard error).

3.4.4. Microphytobenthic (MPB) Community

3.4.4.1. Correlations

Chlorophyll *a*, carbohydrate and protein concentrations were all found to have significant weak positive correlations with one another (Figure 3.29).

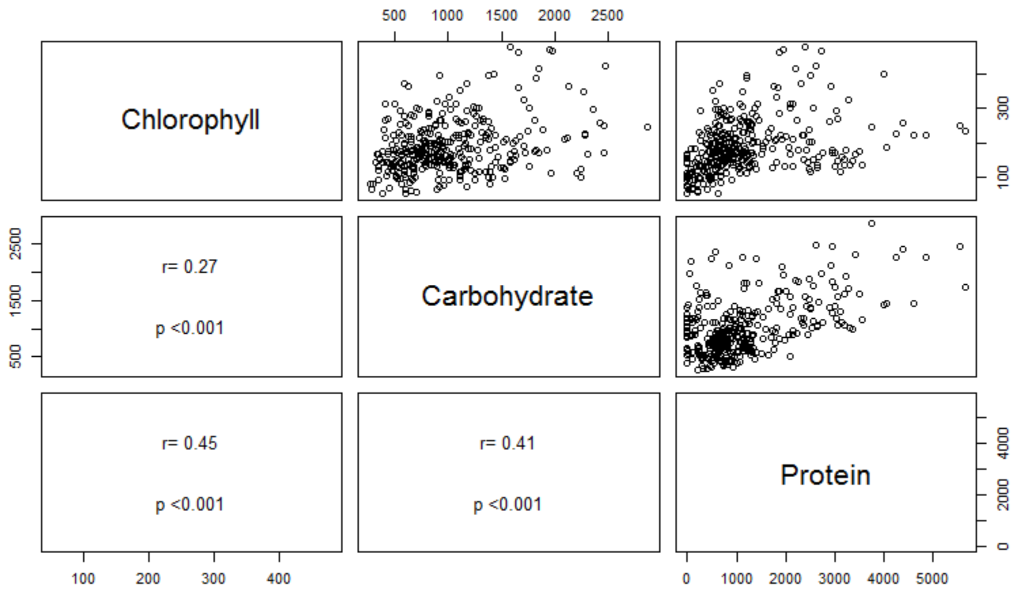


Figure 3.25: Scatter plot (upper panel) and Spearman's rank correlations with statistical significance (lower panel) between measures of microphytobenthic community: chlorophyll *a*, colloidal carbohydrate and protein concentrations (mg m^{-2}).

3.4.4.2. Chlorophyll *a* – Three-Year Time Series

No significant differences were found for chlorophyll *a* concentration among years ($H_2 = 3.13$, $p > 0.1$). A significant difference among sites was found ($H_5 = 16.32$, $p < 0.01$) with *post hoc* Dunn's test confirming that the bare mud site had a significantly higher chlorophyll *a* concentration than all sites except for the natural ($p < 0.005$), however when examining the chlorophyll *a* concentration in year 2012 (Figure 3.26) the concentration was higher at the natural site than at the bare mud site.

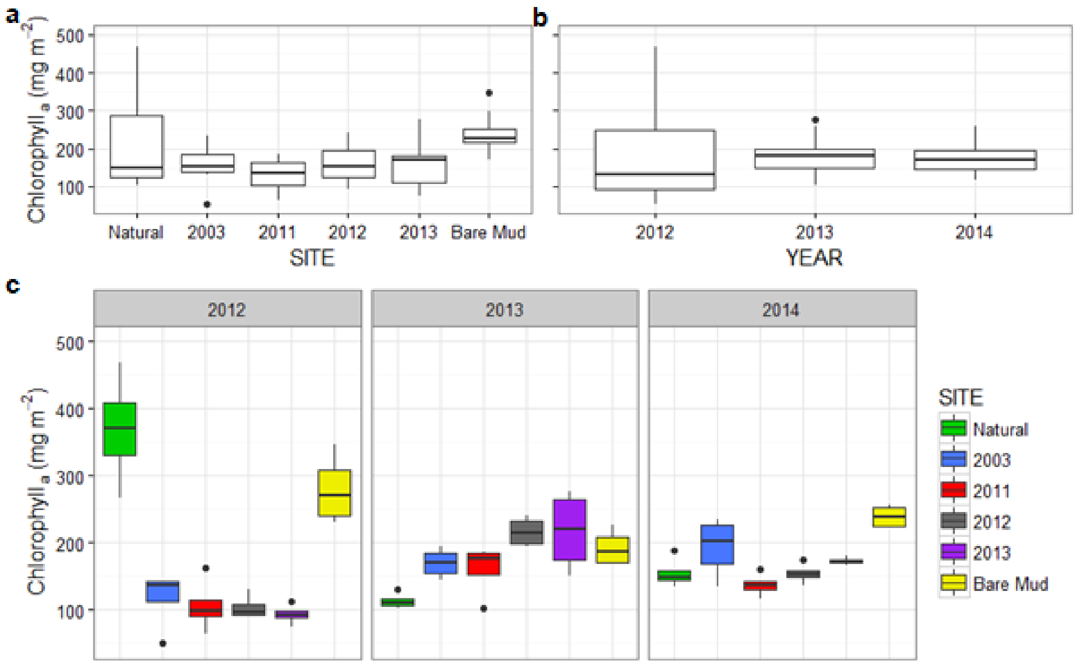


Figure 3.26: Boxplots of surface sediment chlorophyll $_a$ concentration (mg m^{-2}) for a) all sites; b) all years and c) all sites and years sampled within the Eden estuary.

Table 3.12: Summary statistics for surface sediment chlorophyll $_a$ concentration (mg m^{-2}): mean and standard deviation for all sites and years sampled within the Eden estuary.

Chlorophyll$_a$ Concentration (mg m^{-2})	**YEAR**			
SITE	**2012**	**2013**	**2014**	**All Years**
Natural	368.5 ± 83.3	113.0 ± 12.2	154.7 ± 22.7	212.1 ± 125.4
2003	117.0 ± 43.9	169.3 ± 22.6	192.6 ± 45.8	159.6 ± 48.2
2011	105.8 ± 41.2	159.9 ± 39.3	137.2 ± 17.4	134.3 ± 38.8
2012	103.8 ± 18.3	216.0 ± 22.5	153.9 ± 15.1	157.9 ± 50.9
2013	93.1 ± 16.2	217.5 ± 60.0	172.6 ± 6.1	161.1 ± 62.8
Bare Mud	279.0 ± 53.3	192.0 ± 28.1	238.8 ± 17.4	236.6 ± 49.5
All Sites	177.9 ± 117.0	177.9 ± 47.8	175.0 ± 40.2	176.9 ± 75.5

3.4.4.3. Chlorophyll *a* – Seasonal Time Series

A GAM model with a Gaussian link function was used to model the surface sediment chlorophyll *a* relationship with site and season from March 2012 to March 2013. The interaction between site and season was found to be significant, with the model with interaction reducing the AIC and improving the deviance explained. A weighted variance structure by season was incorporated into the model due to different seasons having different variances. The 'VarIdent' function was used which allows for each level of a factor to have a different variance (Pinheiro and Bates, 2000). Smoother terms accounting for the differences between seasons for sites were found to contribute significantly to the model (Figure 3.31, $p < 0.001$) and the model had an adjusted r^2 of 0.401.

Significant differences were found between sites ($F_{5, 288} = 9.70$, $p < 0.001$). The natural site (202.8 mg m^{-2}) had a higher chlorophyll *a* concentration than all the planted sites. The differences observed between the natural and 2003 and 2012 sites were not significant (181.0 mg m^{-2}, $t=1.81$, $p > 0.05$ and 179.3 mg m^{-2}, $t = 1.94$, $p > 0.05$ respectively). The natural site did differ significantly from the 2011 site (174.5 mg m^{-2}, $t = 2.34$, $p < 0.05$) and the 2013 site (155.4 mg m^{-2}, $t = 3.77$, $p < 0.001$). All planted sites were found have a significantly lower chlorophyll *a* concentration compare to the bare mud site ($p < 0.0001$) which had the highest chlorophyll concentration (235.6 mg m^{-2}).

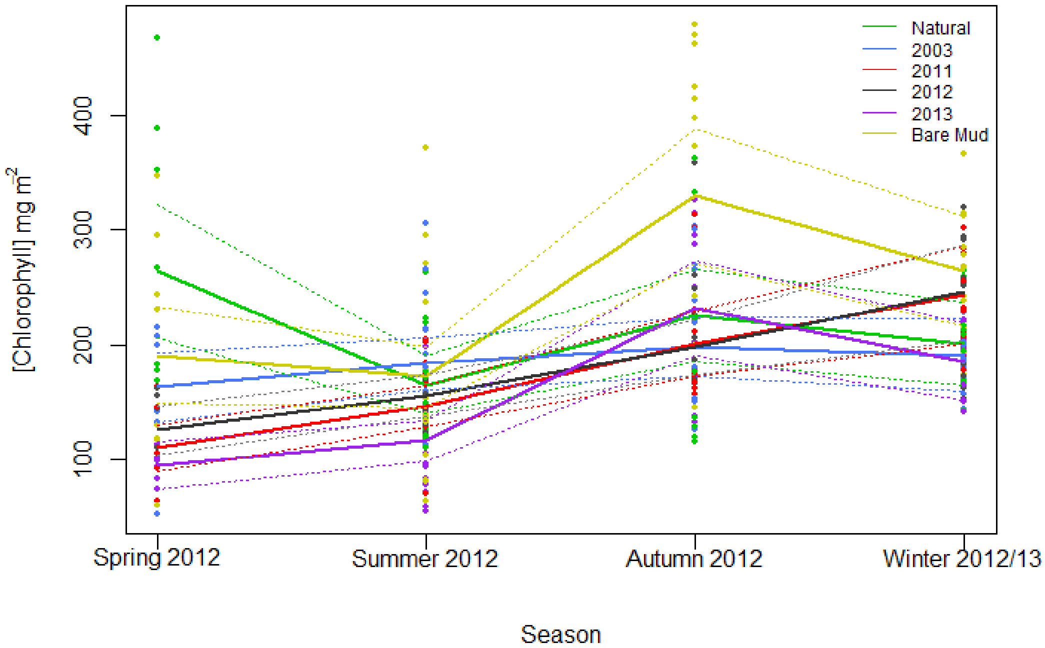


Figure 3.27: Changes in surface sediment chlorophyll *a* concentration over seasons for sites in the Eden estuary. Plotted using a Gaussian Generalised Additive Model with link function. Points represent data. Solid lines represent model plot. Dashed lines represent confidence intervals (2 x standard error).

3.4.4.4. Colloidal Carbohydrate Concentration – Three-Year Time Series

A significant difference was found for carbohydrate concentration among years (H_2 = 21.05, $p < 0.001$). *Post hoc* Dunn's test confirmed that year 2014 had a higher carbohydrate concentration (1557.9 ± 483.6 mg m^{-2}) when compared to years 2012 and 2013 ($p < 0.005$; 1119.6 ± 569.2 mg m^{-2}, 873.0 ± 321.8 mg m^{-2} respectively). Years 2013 and 2014 were not significantly different from one another.

A significant difference was found for carbohydrate concentration among sites (H_5 = 14.223, $p < 0.05$). A *post hoc* Dunn's test confirmed that the bare mud site which had the highest concentration (892.6 ± 655.9 mg m^{-2}) had significantly higher carbohydrate concentrations than site 2003 and 2012 ($p < 0.05$) which had the lowest two concentrations (892.6 ± 455.0 mg m^{-2} and 979.2 ± 399.4 mg m^{-2}, respectively). No other sites were significantly different from one another.

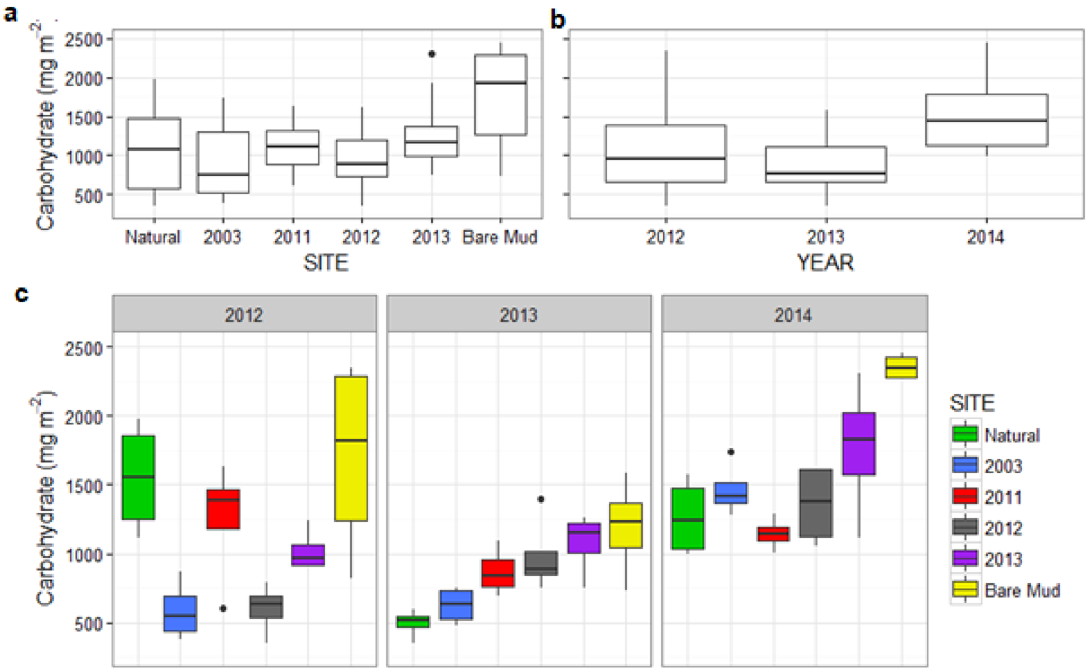


Figure 3.28: Boxplots of surface sediment carbohydrate concentration (mg m^{-2}) for a) all sites; b) all years and c) all sites and years sampled within the Eden estuary.

Table3.13: Summary statistics for surface sediment carbohydrate concentration (mg m^{-2}): mean and standard deviation for all sites and years sampled within the Eden estuary.

Carbohydrate Concentration (mg m^{-2})	**YEAR**			
SITE	**2012**	**2013**	**2014**	**All Years**
Natural	1549.2 ± 409.4	495.3 ± 103.5	1264.0 ± 289.8	1102.8 ± 536.4
2003	588.1 ± 218.3	625.5 ± 135.1	1464.2 ± 196.9	892.6 ± 455.0
2011	1254.7 ± 449.5	868.4 ± 172.4	1144.8 ± 118.5	1089.3 ± 309.6
2012	602.0 ± 186.5	979.7 ± 284.5	1356.0 ± 300.3	979.2 ± 399.4
2013	1021.6 ± 154.9	1079.0 ± 226.2	1766.0 ± 499.3	1288.9 ± 461.8
Bare Mud	1701.7 ± 733.9	1190.2 ± 354.1	2352.4 ± 93.0	1748.1 ± 655.9
All Sites	1119.6 ± 569.2	873.0 ± 321.8	1557.9 ± 483.6	1183.5 ± 543.7

3.4.4.5. Colloidal Carbohydrate Concentration – Seasonal Time Series

A GAM model with a Gaussian link function was used to model the surface sediment carbohydrate concentration relationship with site and season from March 2012 to March 2013. The interaction between site and season was found to be significant, with the model with interaction reducing the AIC and improving the deviance explained. Smoother terms accounting for the differences between seasons for sites were found to contribute significantly to the model (Figure 3.33, $p < 0.05$) and the model explained 33.7% of the deviance with an adjusted r squared of 0.269.

Significant differences were found between sites ($F_{5, 288} = 3.68$, $p < 0.005$). The natural site only differed significantly from site 2003 ($t = 2.06$, $p < 0.05$) which had the highest carbohydrate concentration (1098 mg m^{-2}). The carbohydrate concentration for all other sites ranged between 825 – 927 mg m^{-2}. The bare mud site only also differed significantly from site 2003 ($t = 3.01$, $p < 0.01$)

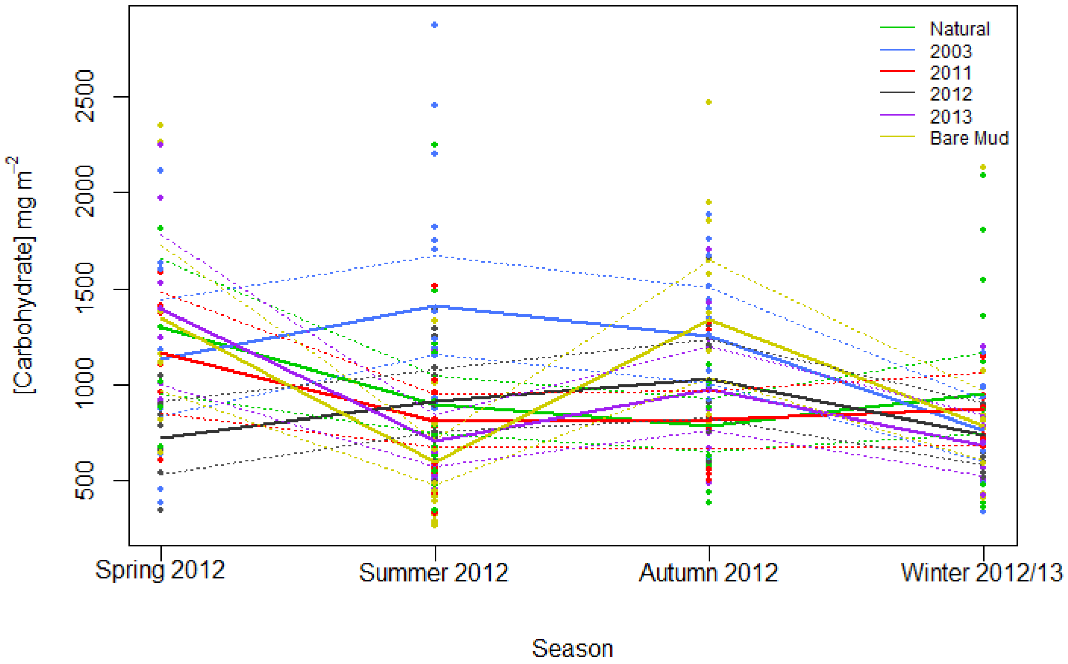


Figure 3.29: Changes in surface sediment carbohydrate concentration over seasons for sites in the Eden estuary. Plotted using a Gaussian Generalised Additive Model with link function. Points represent data. Solid lines represent model plot. Dashed lines represent confidence intervals (2 x standard error).

3.4.4.6. Protein – Three-Year Time Series

A significant difference was found for protein concentration among years (H_2 = 52.36, $p < 0.0001$). A *post hoc* Dunn's test confirmed that all three years were significantly different from one another. Year 2012 had the lowest protein concentration (411.1 ± 612), followed by year 2013 (799.8 ± 455) and year 2014 had notably higher values (3605.7 ± 866).

No significant differences were found among sites for protein concentration (H_5 = 3.15, $p > 0.1$).

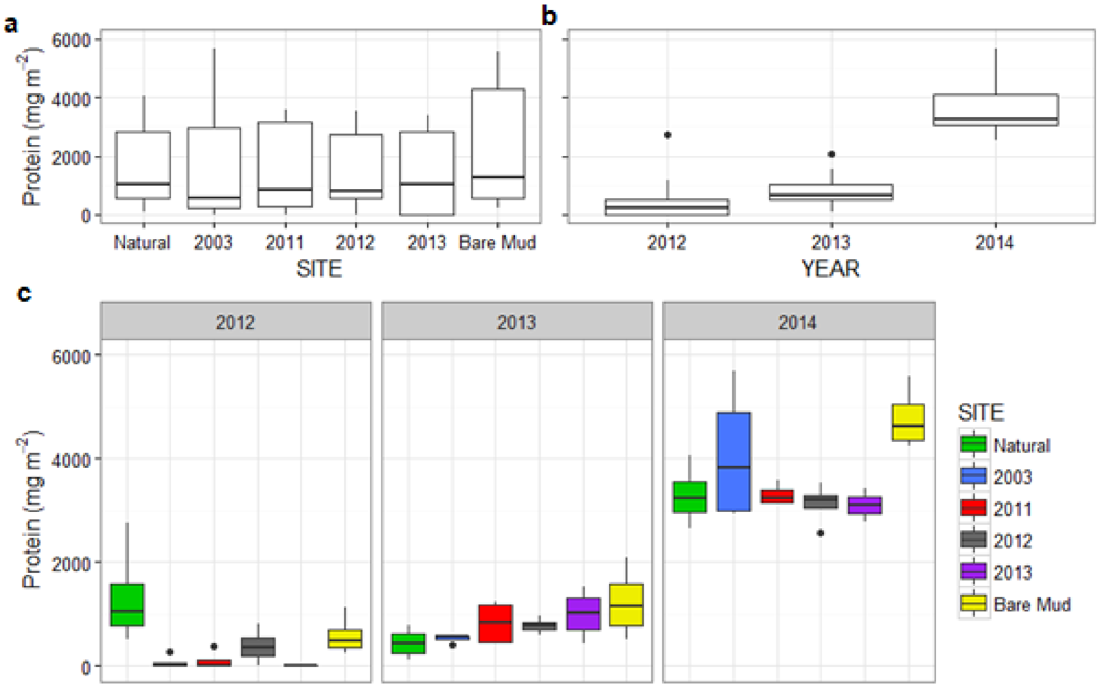


Figure 3.30: Boxplots of surface sediment protein concentration (mg m^{-2}) for a) all sites; b) all years and c) all sites and years sampled within the Eden estuary.

Table 3.14: Summary statistics for surface sediment protein concentration (mg m^{-2}): mean and standard deviation for all sites and years sampled within the Eden estuary.

Protein Concentration ($mg\ m^{-2}$)	YEAR			
SITE	**2012**	**2013**	**2014**	**All Years**
Natural	1329.6 ± 981.6	440.9 ± 302.8	3288.2 ± 595.6	1686.3 ± 1388.5
2003	71.8 ± 143.6	526.4 ± 85.1	4062.6 ± 1328.5	1553.6 ± 1990.0
2011	106.8 ± 188.1	826.8 ± 430.6	3295.0 ± 204.0	1409.5 ± 1450.9
2012	371.8 ± 337.7	771.5 ± 158.5	3121.7 ± 401.3	1421.7 ± 1299.0
2013	0.0 ± 0.0	1006.1 ± 480.2	3099.3 ± 279.1	1368.5 ± 1379.2
Bare Mud	586.7 ± 376.4	1227.4 ± 686.9	4767.3 ± 594.3	2193.8 ± 1987.7
All Sites	411.1 ± 619.9	799.8 ± 454.8	3605.7 ± 865.9	1605.5 ± 1577.5

3.4.4.7. Protein – Seasonal Time Series

A GAM model with a Gaussian link function was used to model the surface sediment protein concentration relationship with site and season from March 2012 to March 2013. The interaction between site and season was found to be significant, with the model with interaction reducing the AIC and improving the deviance explained. Smoother terms accounting for the differences between seasons for sites were found to contribute significantly to the model (Figure 3.35, $p < 0.01$) and the model explained 37.5 % of the deviance with an adjusted r squared of 0.331. There were no significant differences found between sites ($F_{5, 288} = 1.48$, $p > 0.05$).

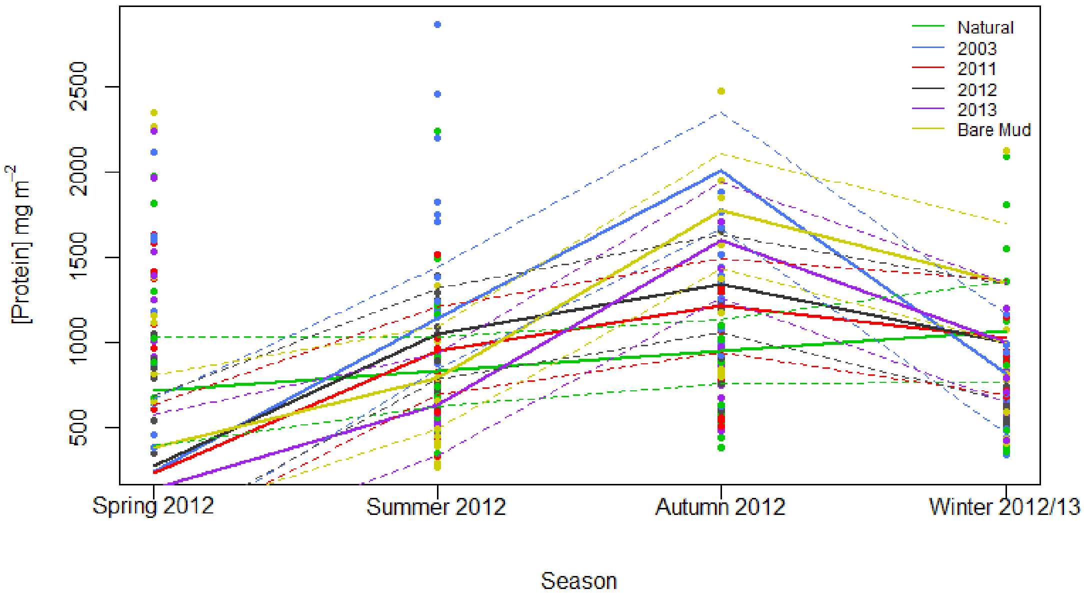


Figure 3.31: Changes in surface sediment protein concentration over seasons for sites in the Eden estuary. Plotted using a Gaussian Generalised Additive Model with link function. Points represent data. Solid lines represent model plot. Dashed lines represent confidence intervals (2 x standard error).

3.5. Discussion

Defining whether habitat restoration or creation has been successful can be very complex, and consequently it is important to define what is meant by “success” for each project in question. This chapter examines whether equivalent ecosystem functioning to natural stands is attained by the planted salt marshes. By comparing the planted sites with the natural sites, we were able to assess whether they were developing similar levels of ecosystem function and whether the ecosystem functions of interest are developing along a similar trajectory. The inclusion of two different time series, one examining a longer-term comparison between similar time points over three years and the other examining the differences throughout a year enables a better understanding of the overall development of the ecosystem function, the inherent variability and the seasonal differences that may occur.

Table 3.15: Outcomes of hypotheses and whether a trajectory progressing towards equivalency with the natural stands is implied by data. R = rejected, NR = not rejected, (R) = rejected but equivalency reached at the oldest planted site (2003) and/or in some time points.

Null hypothesis:	**Proxy**	**Three-year time series**	**Seasonal time series**	**Trajectory implied?**
No significant difference in plant height or density from natural marshes	Plant height	(R)	(R)	Yes ~ 10 y
	Plant density	R	R	Yes > 11 y
No significant difference in sediment stability from natural marshes or bare mud flat. CSM	Erosion threshold	R	NR	No
	Shear stress	(R)	R	Inconclusive
No significant difference in grain size, water content, mud content, organic matter content from natural marshes or bare mud flat	Sediment texture, D_{50}, mud, organic and water content	R	R	No
No significant difference in surface sediment chlorophyll a or EPS concentration from natural marshes or bare mud flat.	Chlorophyll *a*	R	(R)	Inconclusive
	Carbohydrate	R	R	No
	Protein	NR	NR	No

3.5.1. Plant Structure

A salt marsh's ability to act as a coastal flood defence is largely due to the plants attenuation of wave energy, with some studies observing up to 60% of wave reduction is due to vegetation (Möller *et al.*, 2014). This dissipation of energy can be attributed to drag caused by the vegetation canopy, wave shoaling/breaking, and in higher energy storm conditions, the removal material from the marsh edge (erosion) (Möller and Spencer, 2002; Ysebaert *et al.*, 2011; Yang *et al.*, 2012; Möller *et al.*, 2014). Monitoring plant height and density and comparing between the natural and planted sites enables the assessment of whether the planted sites attenuate waves to an equivalent level as the natural site.

The null hypotheses that planted marshes will not show any significant difference in plant height or density from natural marshes can be rejected for both time series as differences were found between planted sites and the natural marsh and bare mudflat (Table 3.15). However, on examining the data for plant height alone equivalence with the natural site was observed at some time points.

In March 2012, the plants of the oldest site (2003) were shorter than those of the natural site, however they were also higher than those of the younger planted sites. This suggests that the plant height at site 2003 was at an intermediate level but progressing along a trajectory that could provide the same level of wave attenuation as the natural site. By March 2013, and repeated in March 2014, the plant height observed at site 2003 and the natural site were comparable suggesting that it takes approximated 10 years for the planted marshes to attain equivalent plant height to the natural salt marshes.

Unlike plant height, plant density had not attained a comparable level by March 2014, but lagged slightly behind in terms of equivalency with the natural site. However, plant density does appear to be progressing along a trajectory that could, over time, allow planted sites to attain an equivalent level to natural salt marsh. The significant strong positive correlation between plant height and density supports this, however, continued monitoring would need to be completed to be certain of this.

Given that this estimates that the length of time it takes for the plant height and density to gain equivalency to that of a natural marsh is at least 10 years, it is unsurprising that the younger planted sites (2011 and 2012) were not equivalent in either height or density compared to the natural site. The success of the 2003 site bodes well for the future development of these younger sites.

The seasonal data for plant height and density supported the estimated 10 years required to gain equivalent height and greater than 10 years to attain equivalent density compared to a natural marsh. The GAM models for plant structure both explained a high proportion of the variability (at least 85%) and a clear seasonal pattern was observed at all sites, with growth in the spring/summer and die back in the autumn/winter as expected. The seasonal pattern was not as obvious for plant density at the youngest two planted sites (2011 and 2012) which could be due to smothering by *Enteromorpha* in the spring and summer. This was noted during sampling, and continues to occur annually (pers. comm. Maynard). The mats that can form on the mud flat and younger sites may prevent the new shoots from emerging and therefore impact the sites restoration. It has been noted that the removal of *Enteromorpha* can lead to greater wash out rates of the plants due to it destabilising the sediment (pers. comm. Maynard). The impact of the *Enteromorpha* on the development trajectory for plant height is not yet known but is a topic to consider when planning future restoration.

In summary, the data suggests that after 10 years, the planted sites would be able to attenuate waves almost as effectively as the natural site. However, due to the slower restoration of plant density compared to plant height there would still be a slight discrepancy between the planted sites and the natural salt marsh. Continued monitoring would be required to be certain that full equivalency in plant structure is restored and subsequently a comparable capacity to attenuate wave and provide coastal flood defence.

Other studies have found that plant structure has taken between 5 and 12 years before the equivalent natural level of plant structure was attained (Levin, Talley and Thayer, 1996; Craft *et al.*, 2003; Garbutt *et al.*, 2006; Wolters *et al.*, 2008; Hughes, Fletcher and Hardy, 2009b; Pétillon *et al.*, 2014) which supports the findings in the Eden Estuary. Few studies have considered when seasonal equivalence is restored. Craft et al (2003) found that it took 8 years for equivalent plant biomass at a specific annual time point, however an additional 4 years was required before seasonal equivalence in biomass was met. Estimates based on managed realignment, which promotes natural colonisation of bare mud flat into salt marsh, have been observed to generally take longer than those using nursery plants brought on in green houses (Moreno-Mateos *et al.*, 2012; Brady and Boda, 2017). The more rapid establishment of greenhouse reared plants is likely due to their more established root system which provides a larger surface area enabling the plants to acquire water and nutrients immediately and therefore send out adventurous roots and establish quickly after planting (pers comm C Maynard). The estimated development trajectory from the Eden appear to be more comparable with those for managed realignment, however, the studies using greenhouse reared plants were located in America and therefore geographical differences should also be considered.

3.5.2. Surface Sediment Stability, Characteristics & MPB

The stability of intertidal sediments is known to be influenced by many physical and biological properties of the sediment (see Grabowski et al., 2011 for overview). Examples of physical properties include grain size and type, water content, bulk density and organic content. Biological properties include the presence of any biofilm and associated EPS and invertebrate feeding, egestion and sediment bioturbation (e.g. burrows). These properties, along with others have been known to vary both temporarily (Taylor and Paterson, 1998; Consalvey *et al.*, 2004; Jesus *et al.*, 2009) and spatially (Guarini *et al.*, 1998; Jesus *et al.*, 2005) from micro to macro scales in the intertidal zone (Yallop *et al.*, 1994; Grabowski, Droppo and Wharton, 2011). The high number of influencing factors and their variability leads to complex interactions and relationships which influence sediment stability (Yallop *et al.*, 1994; Paterson *et al.*, 2000; Yallop, Paterson and Wellsbury, 2000; Grabowski, Droppo and Wharton, 2011; Malarkey *et al.*, 2015; Chen *et al.*, 2017). For this reason, when comparing changes in sediment stability and the MPB community between the restored sites and natural, changes occurring simultaneously in the surface sediment characteristics need to be taken into account.

The variability and complexity of these properties both temporally and spatially was demonstrated by the high level of variation within the data, the need to group the data by season for the 13-month time series and the relatively low deviance explained (33.7 – 54.0%) within the GAM models using this data (adjusted r^2 0.411 - 0.490). In addition, the significant correlations found between many of the sediment characteristics demonstrate that most of the properties co-vary. The high variability meant that observing any trends in the sediment stability, surface sediment characteristics or MPB community was complicated by the interaction and relationships between and within these properties.

3.5.2.1. Sediment Stability

The null hypothesis that the planted salt marshes would not show any significant difference from the bare mud and natural marshes can be rejected for the three-year time series but not the seasonal time series for erosion threshold (Table 3.15). In the three-year time series the bare mud site had the lowest erosion threshold and differed from the 2003 and natural sites which had the highest erosion thresholds. A gradient was observed with natural marsh and older planted sites having a higher erosion threshold declining to the youngest planted site and bare mud flat having the lowest erosion threshold. Plant density and height could explain the differences in the erosion threshold, however differences in sediment characteristics mean this relationship is not simple (Stal, 2010; Grabowski, Droppo and Wharton, 2011). Year and time were significant in both data sets but no seasonal trend could be observed which is likely due to the high natural variability in the data.

The null hypothesis that the planted salt marshes would not show any significant difference from the bare mud and natural marshes can be rejected for both the three-year time series and seasonal time series for shear strength (Table 3.15). Opposite to erosion threshold, the natural site had a lower shear strength than all other sites; in the seasonal time series this was significant for all sites. In the three-year time series it was not significant for the oldest planted site (2003) which could be due to the extended time series or the lack of consideration of a seasonal variation. The high variability in the data and changes in other sediment characteristics makes determining a reason impossible at this time.

3.5.2.2. Sediment Characteristics

Significant differences were found between all or some of the planted sites when comparing them to the natural salt marsh and bare mudflat for all sediment characteristics measured in this study. This allows the rejection of all the null hypotheses that the planted salt marshes would not show any significant difference from the bare mud and natural marshes for all sediment characteristics and in both data sets where applicable (Table 3.15). Significant differences appeared to be driven by sediment texture instead of age of planted site.

Changes in sediment texture at most sites were observed for the three-year time series. Although the data was not available for the seasonal time series, evidence of the sediment texture and D_{50} altering over the period was established through the March 2012 and March 2013 data. The highly significant relationships observed between sediment texture groups and other sediment characteristics, combined with the strong to moderate significant correlations observed between sediment characteristics made interpreting and relating any observed differences in site to a development trajectory challenging. Consequently, proposing a trajectory or timeline for equivalence is not rational. However, the changes in sediment characteristics can assist in explaining the patterns observed for sediment stability.

For the three-year data set, the bare mudflat was found to have significantly higher water content than all sites and significantly smaller D_{50} than all sites except 2003. Both of these characteristics have been found to be properties of sediment with a low erosion threshold such as that observed for the bare mud site (Paterson *et al.*, 2000; Grabowski, Droppo and Wharton, 2011). The mud and organic content were not found to differ between any site except for 2013 which had the lowest content for both properties. The natural site was found to have a significantly higher D_{50} when compared to all sites except 2013, however when examining this in more detail, the natural site also had a much greater variability than any other site with much larger grain size in year 2013. Similar to the bare mud site, mud and organic content only differed from site 2013 which had the lowest content for both properties. The natural site was found to have one of the higher organic contents and a mid-mud content, both properties associated with higher erosion thresholds which were observed at the natural site. Although the water content did not differ significantly from the other planted sites it was the second highest (after bare mud).

Site 2013 was found to differ significantly from both the bare mud and natural sites for several of the properties having the lowest mud, organic and water content and the second highest D_{50}. All of these properties except low water content are associated with low erosion thresholds which was observed at this site (Paterson *et al.*, 2000; Grabowski, Droppo and Wharton, 2011). Site 2013 was located the furthest from the mouth of the river and the furthest from any natural marsh. When considering the geographical location of the planted sites, a spatial gradient was evident, with the sites closest to the mouth of the river and a natural *Pucinella* marsh having a higher mud and organic content and smaller D_{50} than those further away. This geographical gradient was also observed in the erosion thresholds observed between sites.

Site 2003 was bordered on three sides by the *Pucinella* marsh and the transference and trapping by the higher plant density present at the site could also explain the significantly smaller grain size and higher organic and mud content. These properties are associated with high MPB biomass and high erosion thresholds and the site was observed to have the highest erosion threshold.

Water content is known to have a significant positive correlation with organic content and decrease with sandier sediments (Grabowski, Droppo and Wharton, 2011) which explain why, when changes in mud, organic and water content occurred, they were generally in the same direction and D_{50} was in the opposing direction. The significant correlations found between these properties were also as expected with mud, organic and water content being positively correlated to one another and all being negatively correlated with median grain size. No significant differences were observed for water content between the planted sites, and there was no apparent gradient for mud and organic content. This could be due to the high short-term variability expected in water content compared to the other sediment characteristics as it is strongly influenced by temperature, humidity and time since emersion, none of which were monitored or controlled for (Davidson *et al.*, 1991; Yallop *et al.*, 1994; Widdows *et al.*, 2007). The significantly higher water content found in the bare mud could be explained by the small grain size and high mud content present, even though the organic content was one of the lowest. Sediment with high water content has been found to be eroded more easily due to it requiring less energy to become entrained and generally being less compacted. Some studies have found that it is the relationship between mud and water content, defined as the mud volume fraction, that is more influential on the erodibility of sediment with a higher erodibility threshold being found for sediment with a higher mud volume fraction (Dickhudt, Friedrichs and Sandford, 2010). Organic content has also been found to correlate positively with erosion threshold for sediment with less than 2 % organic content being considered more erodible (Grabowski, Droppo and Wharton, 2011). All sites in this study had an organic content less than 2 %.

Sediment texture, which describes whether the sediment is predominantly sandy or muddy was found to differ significantly for many of the sediment properties including median gran size, mud, organic and water content. Sandy sediments which have a larger grain size and lower mud content are less cohesive and have lower sediment stability than muddier samples. Mud and organics have a smaller grain size than sand therefore the relationships observed between sediment texture, mud and organic content were as expected. For this reason, sediment texture provides useful information when interpreting sediment stability with changes in sediment texture observed to change alongside water, mud and organic content. This is a relationship that has been observed in other studies of cohesive sediment (Grabowski, Droppo and Wharton, 2011).

The interactions and changes over time observed within sites can largely be described by changes in the sediment texture. Bare mud and the oldest site (2003) were the only sites not to change sediment texture over the three year time points. The sediment texture for the three youngest planted sites which are all geographically closest to one another and backed by a sea wall, followed the same trend having muddier sediment in year 2013 when compared to years 2012 and 2014. Site 2013 which is the furthest from the natural marsh remained the sandiest of the three over all three years. Although the oldest site (2003) did not change in sediment texture the D_{50} did decrease slightly in year 2013. The natural site also changed texture becoming sandier in year 2013 and with the largest grain size of all sites observed here. A much larger change in the D_{50} was also observed at the natural site compared to the other sites over the three year period, with the sites' standard deviation being at least three times larger than for any other site. Although the same sediment texture was observed for the bare mud site throughout the years sampled, the D_{50} did increase in year 2013. These changes in sediment texture and grain size over time and space can likely be attributed to the prevailing weather or riverine input which may alter currents within the estuary (Lubarsky *et al.*, 2010; Chocholek, 2013). A better understanding of how the currents change within the estuary could help in understanding any changes in the sediment stability over the seasonal time series for which sediment texture, D_{50} and mud content data are not available.

Seasonal data was available for organic and water content. The geographical gradient observed for organic content in the three-year data set was not present in the seasonal data set, however the three youngest sites were always grouped together. No clear seasonal trend was observed for organic or water content when considering all sites, however the oldest site (2003) did seem to peak in summer for both properties which is where the highest variation in data was found. The high amount of variability and low deviance explained by all seasonal models demonstrates the complexity and natural variability of sediment characteristics. Due to this, it is difficult to draw any strong conclusions from this data set and how the sediment variables may influence sediment stability.

3.5.2.3. MPB

It would not necessarily be expected for there to be a difference in the MPB measures between bare mud and salt marsh since previous studies have found that the microalgal biomass has generally been comparable (Underwood, 1997). Where differences have been found, salt marsh had a higher microalgal biomass which was attributed to the protection from resuspension offered by the plant canopy. This difference has been hypothesised to be neutralised by the increased shading where the plant canopy exists (Underwood, 1997).

The null hypothesis that the planted marshes do not differ significantly from the natural marsh or bare mud flat can be rejected for chlorophyll and carbohydrate concentrations but not for protein concentration for both time series (Table 3.15). The natural site did not differ significantly from any sites for chlorophyll, carbohydrate or protein concentrations for the three-year time series. Despite the bare mud site having the lowest erosion threshold, it had the highest concentrations for all MPB measures, with the chlorophyll concentration found to be significantly higher than all planted sites, and carbohydrate concentration significantly higher than sites 2003 and 2013. The natural and bare mud sites, which are located next to one another and at least 1 km from the planted sites, both had mean chlorophyll concentrations at least 50 mg m^{-3} higher than the planted sites whose mean concentrations ranged between 134 – 161 mg m^{-3}. It is unlikely that the higher concentrations observed at the natural site were a result of the increased protection from resuspension offered by the plant canopy as this was not observed at the 2003 site, which had almost comparable measures of plant structure to the natural site. This would also not explain why the bare mud site had the highest concentrations. It is more likely that the difference could be attributed to sediment characteristics and the distance between the planted sites and natural sites. It is possible that additional plant matter incorporated into the sediment could lead to higher chlorophyll *a* at both sites. However, if distance is contributing to the differences observed, the lack of a significant difference in the natural site from the planted sites could be attributed to the variation being at least twice that of any other site.

The differences in concentrations between years match the pattern observed in many of the sediment characteristics with sandier sediment at the same site generally having a lower chlorophyll concentration. This relationship has been observed in other studies with MPB biomass found to correlate positively with grain size (Paterson *et al.*, 2000) and is thought to be due the different types of diatom communities dominating in in different sediment types: epipsammic in sandy sediments and epipelic in muddier sediments (Delgado et al., 1991). The sediment type and grain size were not the only properties influencing the changes in chlorophyll though as despite the natural site having the largest D_{50} by approximately 50 µm in year 2013 it did not have the lowest chlorophyll concentration. MPB biomass has also been found to correlate positively with water content and grain size (Paterson *et al.*, 2000) and to have higher values in muddier sediments with a low D_{50} (Underwood and Smith, 1998).

The same geographical trend with the natural and bare mud sites having higher levels than the planted sites was observed in the seasonal time series and in the three-year time series. The oldest site (2003) had the highest erosion threshold and was the only site to differ significantly from the other planted sites, also having the highest carbohydrate concentration. It was also found to have the highest organic and water contents suggesting that the differences are due to changes in sediment properties. Protein was not found to differ at all between sites, but also had the highest concentrations at site 2003.

The ranking of carbohydrate and protein concentrations in the three-year time series differed when compared to chlorophyll *a* concentration despite chlorophyll *a* having been found to correlate strongly with colloidal carbohydrate and protein concentrations in a number of studies (Underwood, Paterson and Parkes, 1995; Underwood and Smith, 1998; Underwood and Paterson, 2003; Grabowski, Droppo and Wharton, 2011). The correlations in this study were all positive and significant but not as strong as some other studies. These differences and weaker correlations could be attributed to changes in the sediment characteristics between sites (Underwood, 1997; Smith and Underwood, 1998; Grabowski, Droppo and Wharton, 2011).

Similar to the seasonal time series data for sediment characteristics, the data for the MPB community showed a high amount of variability and the GAM models explained a low level of deviance (r^2 0.269 - 0.401). This high variation can be attributed to spatial and temporal variation and interactions with the sediment characteristics.

No seasonal trends across sites were observed for MPB and EPS measures with some sites varying in concentration and other remaining more constant. The variation observed in winter was less than for the other months. MPB seasonal trends have observed in a few studies with peaks occurring in spring and summer; however, the influence of feeding on or bioturbation of the sediment by other organisms has been hypothesised to cloak changes in MPB and EPS measures (Underwood, 1997; Widdows *et al.*, 2006).

Despite the data having high variability and the deviance explained in the GAM models being low, the differences observed between sites and over time for MPB measures support the idea that variations in multiple sediment properties influence the MPB community alongside temporal and spatial changes. This makes interpreting changes in sediment stability challenging.

3.5.3. Restoration of Ecosystem Functioning

This study indicates that wave attenuation can be restored to levels almost comparable to that provided by natural salt marshes after 10 years with plant height being comparable and plant density being slightly lower than that of the natural site. Measures for sediment composition and MPB biomass revealed high spatial and temporal variability with no trends in sediment stability being related to time since planting. The development trajectory for restoration of sediment stability was inconclusive.

3.6. Conclusions

- Plant structure for the planted sites was developing along a trajectory expected to attain comparable ecosystem function to natural marsh site suggesting that equivalent wave attenuation will be reached.
- Plant height attains comparable measures to the natural site, including seasonal differences, 10 years after planting.
- Plant density takes more than 11 years to attain comparable measures to that of the natural marshes.
- Understanding the development trajectory of sediment stability was not possible due to the spatial and temporal natural variability in the data and the highly complex relationships between sediment characteristics and MPB and no trajectory is implied.
- Sites with high organic content, mud content and low D_{50} were generally found to have higher erosion thresholds.
- Geographical distances between sites and distance from natural salt marsh were found to be influential in determining differences in sediment characteristics and MPB measures.

Chapter 4: The Benthic Macrofaunal Community in Restored Salt Marshes, Eden Estuary

4.1 Introduction

Any environment, incorporating its biodiversity, has both intrinsic and utilitarian value. In the past, approaches to valuing and protecting nature for intrinsic reasons have not been effective, with continuing loss and degradation of over 60% of the world's ecosystems recorded (Millennium Ecosystem Assessment, 2005c). Salt marshes are no exception to this trend and are considered some of the most impacted ecosystems in the world (Gedan, Silliman and Bertness, 2009). The ecosystem service approach has provided a utilitarian argument for conserving biodiversity, and more widely the environment, by placing nature in the context of ecosystem services (ES) and their related impact on human well-being (R Costanza *et al.*, 1997; Secretariat of the Convention of Biological Diversity, 2000; Millennium Ecosystem Assessment, 2005a; Haines-Young and Potschin, 2010; TEEB, 2010; UK National Ecosystem Assessment, 2011a; Cardinale *et al.*, 2012). Interest in restoring and creating salt marsh to replace the ecosystem service provision lost through habitat loss and degradation has received increasing attention over the past decades (Zedler and Callaway, 1999; Millennium Ecosystem Assessment, 2005b; Bullock *et al.*, 2011; Moreno-Mateos *et al.*, 2012).

Human well-being is not directly dependent on biodiversity, but instead on the functions of an ecosystem (Figure 4.1). Ecosystem functions (EF) can include the structures and processes produced or undertaken by the compliment of living organisms (biodiversity) and their interactions with abiotic and biotic components of an ecosystem. It is these EF that underpin the provision of the final ES that support human well-being. A clear and positive link between biodiversity and ecosystem functioning has been demonstrated in many experimental and meta-analysis studies (Loreau *et al.*, 2001; Hooper, Chapin III and Ewel, 2005;

Balvanera *et al.*, 2006; Worm *et al.*, 2006; Cardinale *et al.*, 2012; Harrison *et al.*, 2014). Costanza et al. (2007) reported that a 1% change in biodiversity in warm ecoregions corresponds to approximately a 0.5% change in the total economic value of ES.

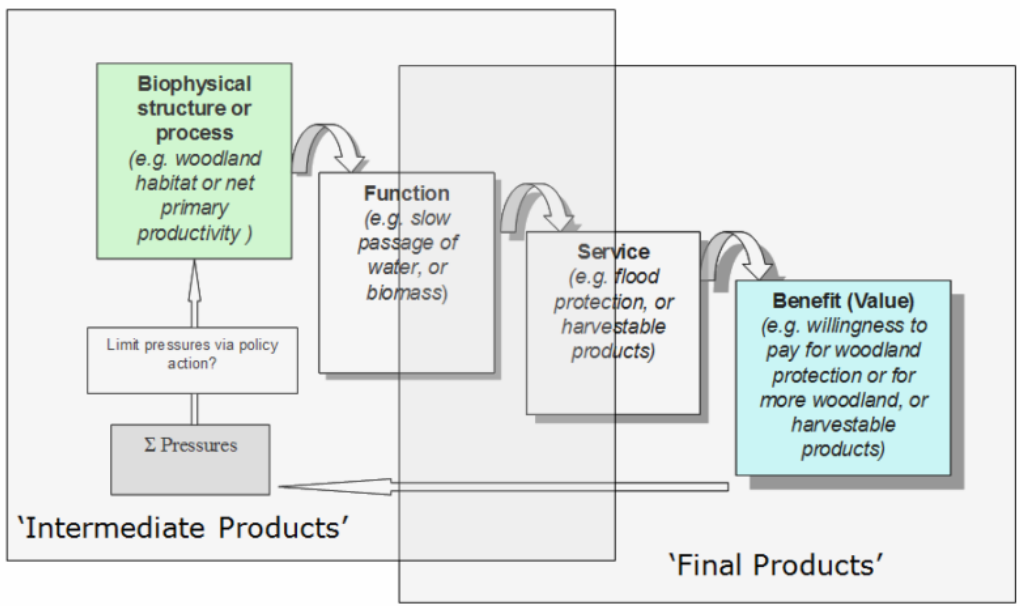


Figure 4.1: The relationship between biodiversity, ecosystem function and human well-being. (Adapted from Haines-Young & Potschin 2010).

Many metrics representing some form of biodiversity exist and have been used to examine its relationship with EF. Several measures of species diversity have been used including functional diversity, species composition and community assemblage comparisons, however the most commonly used metric remains species richness (Cardinale *et al.*, 2012; Balvanera *et al.*, 2014). The biodiversity metric used does not appear to change the resulting relationship with almost all studies having found that a loss in biodiversity equates to a loss in EF (Balvanera *et al.*, 2014). The scale over which biodiversity is measured has been found to influence the strength of the relationship between biodiversity and EF, with species and community level characteristics demonstrating a stronger positive relationship to EF than ecosystem and landscape level (Balvanera *et al.*, 2014).

The benthic macrofaunal community contributes to a wide number of ecosystem services within salt marshes. For example, many of the oligochaetes and polychaetes are important detritivores, breaking down organic matter and releasing nutrients into the system; many are also ecosystem engineers that burrow, aerating the soil and burying carbon. Functions such as these enhance plant production and subsequently can lead to increases in plant biomass. They also provide an important food source for birds and fish fulfilling an important trophic link between primary producers and higher trophic levels. When restoring or creating salt marshes it is important to understand whether these benthic macrofaunal communities are also restored and provide comparable ecosystem functions.

There are a limited number of existing studies investigating the changes in macrofaunal community structure within restored salt marshes in Europe, and the majority of those are based on managed realignment as this is the principle form of salt marsh restoration in this region. Garbutt et al. (2006) reported that the initial colonisation by invertebrates at a managed realignment site in south-east England was rapid, however after seven years the species richness and abundance remained below that of the natural control sites. Curado et al. (2014) monitored a planted site in Spain for three years and found that after this time benthic macrofaunal had attained an intermediate state compared to the natural marsh with comparable abundance, similar diversity and higher species richness than the natural site. They also noted that the species composition at the planted site differed from that of the natural site.

More extensive research has taken place on created marshes in North America where planting is a more common method of restoration with macrobenthic invertebrate density and species richness reaching equivalent measures after approximately eight years (Levin and Talley, 2002; Swamy *et al.*, 2002; Craft and Sacco, 2003; Craft *et al.*, 2003). However, Swamy et al. (2002) also observed that differences in species composition between the reference site and the restored sites remained after this time with functional recovery still not being reached after 20 years. A meta-analysis modelling recovery trajectories for data from all forms of wetland worldwide estimated that it took 5 – 10 years for macroinvertebrate assemblages from restored sites to converge with reference assemblages but that average values would never reach reference levels (Figure 4.2) (Moreno-Mateos *et al.*, 2012).

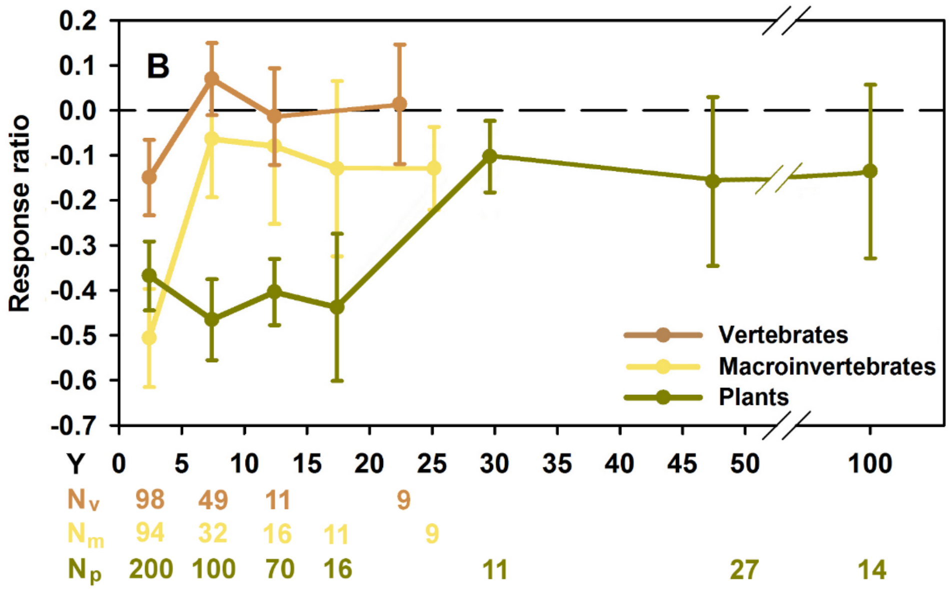


Figure 4.2: Chrono sequences indicating the recovery trajectory of created and restored wetlands estimated using meta-analysis for the major biological structure components (Means ±SE). (Taken from Moreno-Mateos et al. 2012).

It appears that the macrobenthic communities colonise alongside salt marsh plant restoration, however the length of time this process takes is unclear, as is the period required for the community to be equivalent in terms of species composition. Despite this, studies indicate that it is likely that functional equivalency is restored, even if the species composition is different. Additional studies are required in order to gain an improved understanding of the potential recovery trajectories for macrofaunal.

4.2 Aim of Chapter

Experimental sites in the Eden Estuary have been successfully transplanted and now accumulate sediment at a rate comparable to or greater than that of a natural salt marsh (Maynard *et al.*, 2011). Results reported in chapter three suggest that plant height equivalent to that of the natural site can be achieved after approximately 10 years and that equivalent plant density takes more than 11 years. This chapter aims to add to this knowledge of the Eden salt marshes by assessing whether the benthic macrofaunal community in the planted salt marshes is also able to attain comparable levels to that of the natural stands.

Data collected at sites planted between 2003 and 2013 were used to assess annual and seasonal trends by comparing biodiversity metrics and community assemblage analysis for the benthic macrofaunal community to natural and bare mudflat sites:

H_0: The planted marshes will not show any significant difference in community assemblage from natural marshes or bare mud flat.

H_0: The planted marshes will not show any significant difference in biodiversity (species abundance and species richness) from natural marshes or bare mud flat.

4.3 Methodology

4.3.1 Sample Collection

Sediment cores (n = 4) were collected at the natural donor marsh site (natural), a bare mud site (bare mud) and sites that were planted in 2003, 2011, 2012 and 2013 (Figure 2.1) every four months between March 2012 and March 2013. An additional collection was made in March 2014 for a three-year dataset. Site 2013 was bare mud at the beginning of the study until it was planted in February 2013. Sediment samples were sieved, preserved and all individuals identified to the lowest possible taxa using a dissecting microscope.

4.3.2 Statistical Analysis

To compare the macrofaunal community composition between sites over time, multivariate analysis was completed using Primer. The same 2 factor design was used for both the three-year data set and the seasonal dataset with site being a fixed factor with six levels (natural stand, planted in 2003, 2011, 2012 and 2013 and bare mudflat) and time being a random factor. The three-year dataset, time had three levels: March 2012, 2013 and 2014; for the seasonal dataset, time had 4 levels: March 2012, July 2012, November 2012 and March 2013. Both factors were orthogonal with 4 replicates for each site at each time point.

Multivariate analysis was performed on square-root transformed data to even out disparity between rare or abundant species. Bray-Curtis similarity matrices (Bray and Curtis, 1957) were generated using the transformed data and non-metric multidimensional scaling (nMDS) plots were visualised and permutational analyses of variation (PERMANOVA) were performed based on these.

nMDS is an ordination method which represents samples as points in low-dimensional space. They are calculated from a resemblance matrix, with the relative distances between points being in the rank order of the relative dissimilarities of the samples. Multiple iterations of the ordination are run to converge on an optimal solution (Clarke and Gorley, 2006). The points on an nMDS plot that are close together represent samples that are very similar in community composition and *vice versa*. A stress value is produced for each plot and is an indication of how well the relationships among samples are represented by the ordination plot. A stress value of less than 0.05 is considered to be an excellent representation, between 0.05 and 0.1 a very good representation, between 0.1 and 0.2 a good representation and above 0.3 as equivalent to random representation of the relationships between samples (Clarke and Gorley, 2006).

PERMANOVA is the multivariate equivalent of analysis of variance (ANOVA) and enables simultaneous testing of one or more response variables to one or more explanatory factors using permutation methods. It uses a resemblance matrix, partitioning data into within and between group variance based on dissimilarities rather than distance (Anderson, Gorley and Clarke, 2008). Random permutations of the data are performed multiple times based on the labels associated with the data to build a distribution analogous to Fisher's F-statistic used in ANOVA. Where this pseudo-F statistic is generated using the correct labels associated with the data is greater than that produced through the permutations the null hypothesis (i.e. due to chance) can be rejected. The p-value is calculated based on the proportion of pseudo-F values generated by permutation and the true pseudo-F value based upon the true data (Anderson, Gorley and Clarke, 2008).

An assumption of PERMANOVA is that sample dispersions are independent and homogenous (Anderson, Gorley and Clarke, 2008). PERMDISP is a routine which test for homogeneity of dispersions. PERMANOVA is considered robust to violations of homogeneity and it is currently not considered compulsory for a non-significant PERMDISP result for PERMANOVA to be accepted as PERMDISP can detect smaller differences in dispersion than PERMANOVA (Anderson, Gorley and Clarke, 2008). Reasoned judgement was used as to whether to accept or reject PERMANOVA results when a significant violation of heterogeneity was found using PERMDISP.

If the PERMANOVA test was rejected, an analysis of similarities (ANOSIM) test was conducted. Like PERMANOVA, ANOSIM is calculated from a resemblance matrix but relies on rank dissimilarities among samples (Clarke and Gorley, 2006). It is based on a scale, R, between -1 and 1. Where R is less than 0.2, differences should be considered as unimportant biologically, where R is between 0.2 and 0.5 the differences are notable but not greatly distinct, and where R is greater than 0.5 there is a reliable difference (Cramb, 2015).

To identify patterns of similarity between sites and time points nMDS plots were visualised and examined for relationships. nMDS visualisation was completed with 50 restarts and the stress value of the iterations was assessed to ensure that the lowest value was calculated at least six times.

PERMANOVA tests were performed with 9999 permutations; all other settings were unchanged. Where significant main effects were found, *post hoc* pairwise comparisons between levels of factors were performed to determine the source of variation. Where the number of possible permutations was less than 100 p-values were generated using Monte-Carlo random draws to construct an asymptotic permutation distribution for the pseudo-F statistic (Anderson, Gorley and Clarke, 2008).

Where PERMANOVA detected a significant interaction, additional nMDS plots of individual time points were visualised to assist in identifying the differences between sites which is the focus of this study. Where clusters were visible in the nMDS plots and significant main effects had been identified using PERMANOVA, SIMPER analysis was utilised to determine which taxa contributed to the apparent sources of variation (Clarke and Warwick, 2011).

In addition to the multivariate analysis, community composition was examined by calculating the mean abundance and species richness per site for each time point. A two-way ANOVA (site and time) was used to compare differences between site, time and the interaction. R-Studio and R were used to conduct this analysis.

4.4 Results

Across all sites and time points a total of 49596 organisms were identified from 120 cores. A total of 31 taxon were identified with annelids, molluscs and most crustacea being identified to species level. Ostracods and insects were identified to class level with nematodes, nemertean and foraminifera being identified to phylum level. A full species list is presented (Table 4.1).

Table 4.1: List of all benthic macrofaunal taxa identified in the Eden estuary across all sites and time points.

Species	Phylum	Sub-phyllum	Class	Sub-class	Order	Family	Genus
Enchytraeidae	Annelida		Clitellata	Oligochaeta	Enchytraeida	Enchytraeidae	
Tubificoides pseudogaster agg.	Annelida		Clitellata	Oligochaeta	Haplotaxida	Naididae	Tubificoides
Tubificoides bendii	Annelida		Clitellata	Oligochaeta	Haplotaxida	Naididae	Tubificoides
Hediste diversicolor	Annelida		Polychaeta	Errantia	Phyllodocida	Nereiddae	Hediste
Eteone longa	Annelida		Polychaeta	Errantia	Phyllodocida	Phyllodocidae	Eteone
Fabricia stellaris	Annelida		Polychaeta	Sedentaria	Sabellidae	Fabriciidae	Fabricia
Fabriciola baltica	Annelida		Polychaeta	Sedentaria	Sabellidae	Fabriciidae	Fabriciola
Manayunkia aestuarina	Annelida		Polychaeta	Sedentaria	Sabellidae	Fabriciidae	Manayunkia
Pygospio elegans	Annelida		Polychaeta	Sedentaria	Spionida	Spionidae	Pygospio
Capitella capitata	Annelida		Polychaeta	Sedentaria		Capitellidae	Capitella
Harpacticoid	Arthropoda	Crustacea	Hexanauplia	Copepoda	Harpacticoida		
Corophium volutator	Arthropoda	Crustacea	Malacostraca	Eumalacostraca	Amphipoda	Corophiidae	Corophium
Gammarus locusta	Arthropoda	Crustacea	Malacostraca	Eumalacostraca	Amphipoda	Gammaridae	Gammarus
Carcinus maenas	Arthropoda	Crustacea	Malacostraca	Eumalacostraca	Decapoda	Carcinidae	Carcinus
Isopod	Arthropoda	Crustacea	Malacostraca	Eumalacostraca	Isopoda		
Ostracod	Arthropoda	Crustacea	Ostracoda				
Insect larvae 1 + 2	Arthropoda	Hexapoda	Insecta				
Insect larvae 3	Arthropoda	Hexapoda	Insecta				
Insect larvae 4	Arthropoda	Hexapoda	Insecta				
Emerging Insect 1	Arthropoda	Hexapoda	Insecta				
Insect 1	Arthropoda	Hexapoda	Insecta				
Insect 2	Arthropoda	Hexapoda	Insecta				
Mite	Arthropoda		Arachnida	Acarina			
Cerastoderma edule	Mollusca		Bivalvia	Heterodonta	Cardiida	Cardiidae	Cerastoderma
Macoma balthica	Mollusca		Bivalvia	Heterodonta	Cardiida	Tellinidae	Macoma
Mytilus edulis	Mollusca		Bivalvia	Pteriomorphia	Mytilida	Mytilidae	Mytilus
Hydrobia ulvae	Mollusca		Gastropoda	Caenogastropoda	Littorinimorpha	Hydrobiidae	Hydrobia
Littorina littorea	Mollusca		Gastropoda	Caenogastropoda	Littorinimorpha	Littorinidae	Littorina
Nematode	Nematoda						
Nemertean	Nemertea						
Foraminifera	Retaria	Foraminifera					

4.4.1 Three-Year Time Points

4.4.1.1 Multivariate Analyses: Community assemblage comparison

The nMDS plot generated for all cores sampled in March 2012, 2013 and 2014 (Figure 4.3) illustrated groupings by sites with the bare mud site being the most distinct, followed by the natural site. The natural site had two points which were distinct from other natural points. All planted sites overlapped with one another to some degree with the oldest site, 2003, forming the most distinct cluster of the planted sites. No obvious grouping between years were present.

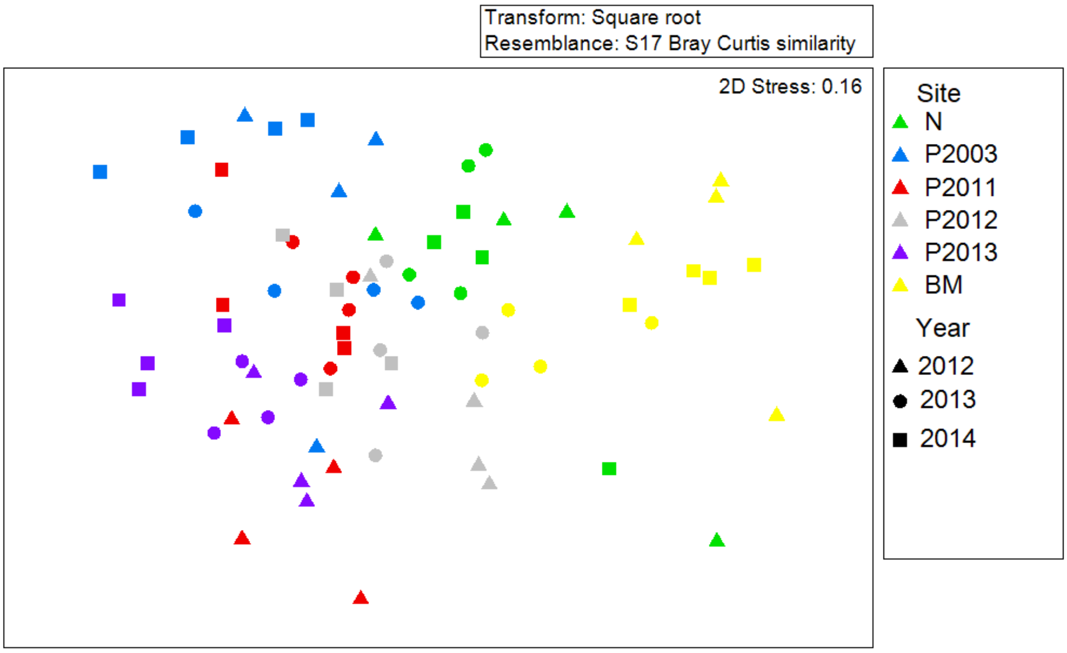


Figure 4.3: Non-metric multidimensional scaling (nMDS) plot of macrofaunal assemblages based on square root transformed abundance data from sites (represented by colour) within the Eden Estuary sampled over a three-year period (represented by symbol). Sites included natural salt marsh stands (N), salt marsh planted in 2003 (P2003), 2011 (P2011), 2012 (P2012) and 2013 (P2013), and a bare mudflat (BM).

PERMANOVA analysis revealed a significant interaction between site and year (pseudo-$F_{10, 54}$ = 2.33, p = 0.0001) and significant main effects for year (pseudo-$F_{2, 54}$ = 8.68, p = 0.0001) and site (pseudo-$F_{5, 54}$ = 7.07, p = 0.0001). The significant main effects should not be interpreted separately due the significant interaction term, making it impossible to interpret the site effects without taking into account the variation between years.

PERMDISP analysis was not significant for the interaction term ($F_{17, 54}$ = 1.66, p(perm) = 0.424) or site ($F_{5, 66}$ = 1.47, p(perm) = 0.311), however it was significant for year ($F_{2, 69}$ = 7.47, p(perm) = 0.049) indicating that variances may not be homogenous across years. Given that PERMANOVA is known to be robust to violations of homogeneity, that PERMDISP is more sensitive to homogeneity that PERMANOVA and that the p value was borderline it was considered acceptable to ignore this violation.

Post hoc pairwise tests for the interaction term determined that differences in community assemblage were consistently found across years between sites. The aims of this study are focussed on assessing the recovery of macrofaunal community composition in the planted sites by comparing them with the natural salt marsh stands and bare mudflat. Therefore, the significant differences observed between years have not been discussed and individual nMDS plots were visualised (Figure 4.4) and 1-way PERMANOVA tests performed (Table 4.2) for each year to enable a more informed comparison between sites.

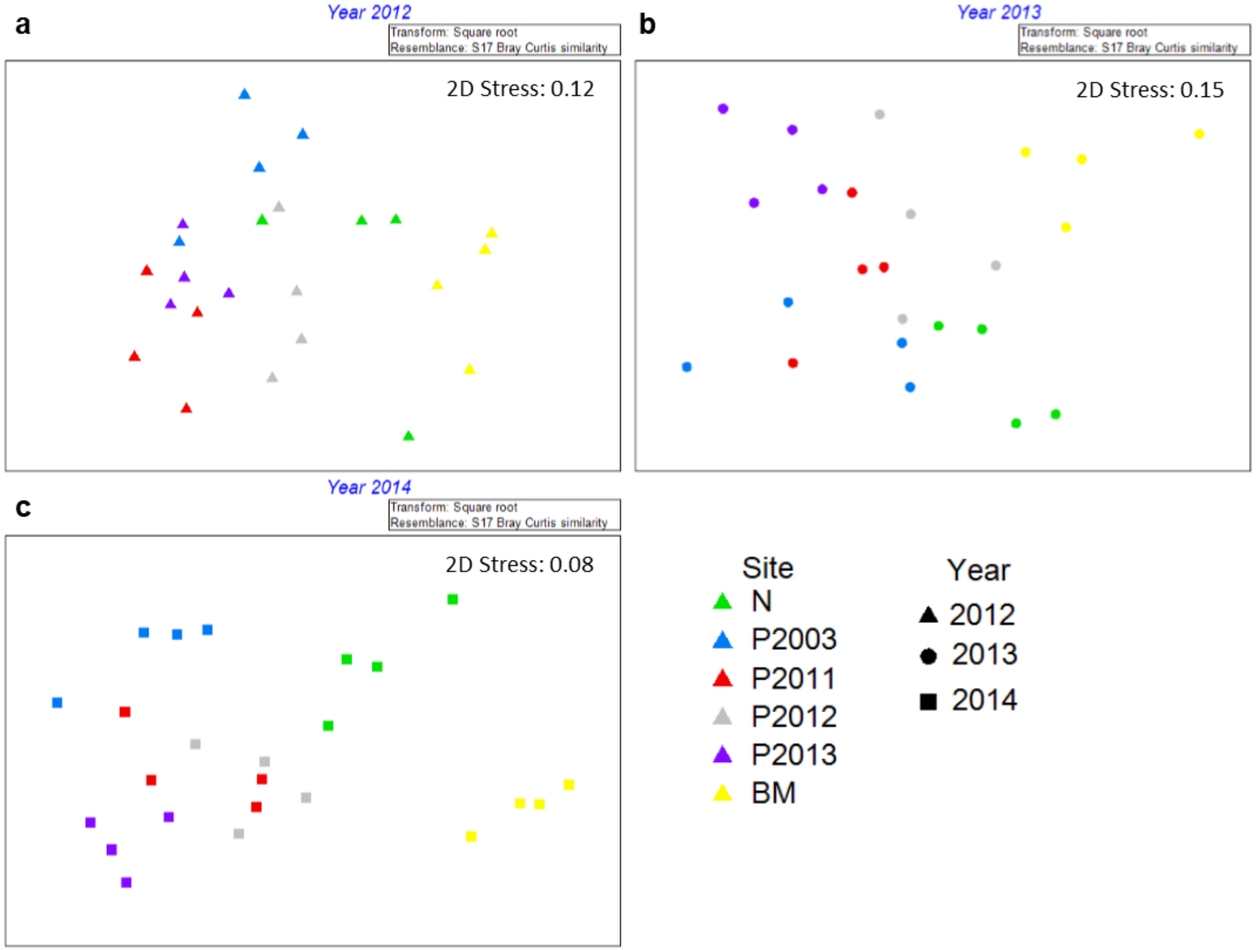


Figure 4.4: Non-metric multidimensional scaling (nMDS) plots of macrofaunal assemblages based on square root transformed abundance data for sites (represented by colour) natural salt marsh stands (N), salt marsh planted in 2003 (P2003), 2011 (P2011), 2012 (P2012) and 2013 (P2013), and a bare mudflat (BM). Individual plots for each time point a) March 2012, b) March 2013, and c) March 2013.

Table 4.2: Summary of PERMDISP and PERMANOVA results for the analysis of differences in macrofaunal community assemblage structure across sites. Tests were run separately for years. *Bold text indicates a significant result.*

Year	**Test**	**df = 5, 18**	**Source of variation**	
			Site	**Residual**
2012	PERMDISP	F	0.77	
		P(perm)	0.83	
	PERMANOVA	MS	3490.2	614.5
		Pseudo-F	5.68	
		P(perm)	**0.0001**	
2013	PERMDISP	F	0.72	
		P(perm)	0.79	
	PERMANOVA	MS	2035.3	345.5
		Pseudo-F	5.89	
		P(perm)	**0.0001**	
2014	PERMDISP	F	1.86	
		P(perm)	0.30	
	PERMANOVA	MS	3746.9	358.0
		Pseudo-F	10.47	
		P(perm)	**0.0001**	

The nMDS plots illustrated clear clustering between sites in all years. PERMANOVA results confirmed this, with site being significant in all three years. PERMDISP indicated that no significant differences were observed in the variance of the community structure between sites in any one year. *Post hoc* pairwise tests (Table 4.3) were performed for all sites to compliment the nMDS visualisation of the community assemblage and directly compare the average similarity in community structure between sites within year.

For years 2013 and 2014 both the natural and bare mud sites differed significantly for all planted sites and one another. This pattern was also generally observed in 2012 with the exceptions of the bare mud and natural sites not differing significantly from one another, and the natural site also not differing significantly from the site planted in 2012. The higher within site variation observed at the natural site in 2012 compared to 2013 and 2014 could explain this change in pattern. The nMDS plot for 2012 (Figure 4.4a) shows one the four natural samples as being distinct from the others.

The bare mud site had the highest dissimilarities in community assemblage with all other sites in any one year, with 2012 and 2014 having very low average similarities. This was also visible in the nMDS plots with the bare mud consistently grouped away from the other sites with the natural sites being the closet cluster. Although the natural site was generally significantly different from all the planted sites, it had a higher similarity in community assemblage with the planted sites than the bare mud site. Although the order of similarity of community assemblage between the natural site and planted sites varied over the years, in general, the sites planted in 2003 and 2012 had a higher similarity than those planted in 2011 and 2013.

Among the planted sites some patterns were observed. The most recently planted site, 2013, always appeared as a distinct cluster on the nMDS plots and generally demonstrated less overlap with the other planted sites. It consistently had the least similarity in community assemblage with site 2003 and the highest similarity with site 2011; this was confirmed in the significance values generated with site 2013 always being significantly different from 2003 and 2012 but not 2011. The oldest planted site, 2003, was significantly different from all other planted sites in 2012 and 2014 and only significantly different from site 2013 in year 2013; this pattern was reflected in the nMDS plots.

Table 4.3: Summary of *post hoc* pairwise comparisons of macrofaunal community assemblage using PERMANOVA for all sites using three-year data. Tests were run separately for years. Similarity: average similarity within/between sites, the colour gradient from green to red represents high to low similarity. p(MC) is the probability calculated using the Monte Carlo method; bold text indicates a significant result.

Year	Site	Natural Stand		P2003		P2011		P2012		P2013		Bare Mudflat
		Similarity	p(MC)	Similarity	p(MC)	Similarity	p(MC)	Similarity	p(MC)	Similarity	p(MC)	Similarity
2012	Natural Stand	57.9										
	P2003	51.9	**0.046**	66.8								
	P2011	43.4	**0.009**	50.7	**0.017**	67.7						
	P2012	55.2	0.093	54.2	**0.028**	57.1	**0.030**	66.5				
	P2013	51.2	**0.018**	55.7	**0.021**	64.3	0.064	59.6	**0.030**	72.4		
	Bare Mudflat	53.9	0.056	37.7	**0.002**	30.1	**0.001**	48.7	**0.008**	35.6	**0.001**	68.6
2013	Natural Stand	77.4										
	P2003	63.2	**0.023**	70.1								
	P2011	66.4	**0.015**	66.8	0.066	75.5						
	P2012	66.0	**0.023**	66.0	0.070	71.1	0.128	72.8				
	P2013	53.8	**0.002**	60.9	**0.011**	70.8	0.065	63.3	**0.010**	74.7		
	Bare Mudflat	59.3	**0.009**	52.8	**0.003**	57.6	**0.002**	59.9	**0.004**	52.5	**0.002**	76.0
2014	Natural Stand	70.5										
	P2003	50.7	**0.001**	70.8								
	P2011	55.2	**0.009**	59.6	**0.017**	71.6						
	P2012	60.4	**0.014**	57.8	**0.007**	73.4	0.415	72.9				
	P2013	41.8	**0.001**	58.1	**0.006**	65.6	**0.011**	64.9	**0.016**	79.0		
	Bare Mudflat	52.5	**0.003**	34.2	**0.001**	40.6	**0.001**	46.1	**0.001**	31.8	**0.002**	79.8

SIMPER analysis supported the dissimilarities in community assemblage between the natural, bare mud and planted sites identified by the PERMANOVA tests. The dissimilarity between the bare mud site and all other sites could largely be attributed to the abundance of insects. The lower abundance of *Corophium volutator* at the bare mud site was also found to be a key contributor to the dissimilarity with the planted sites.

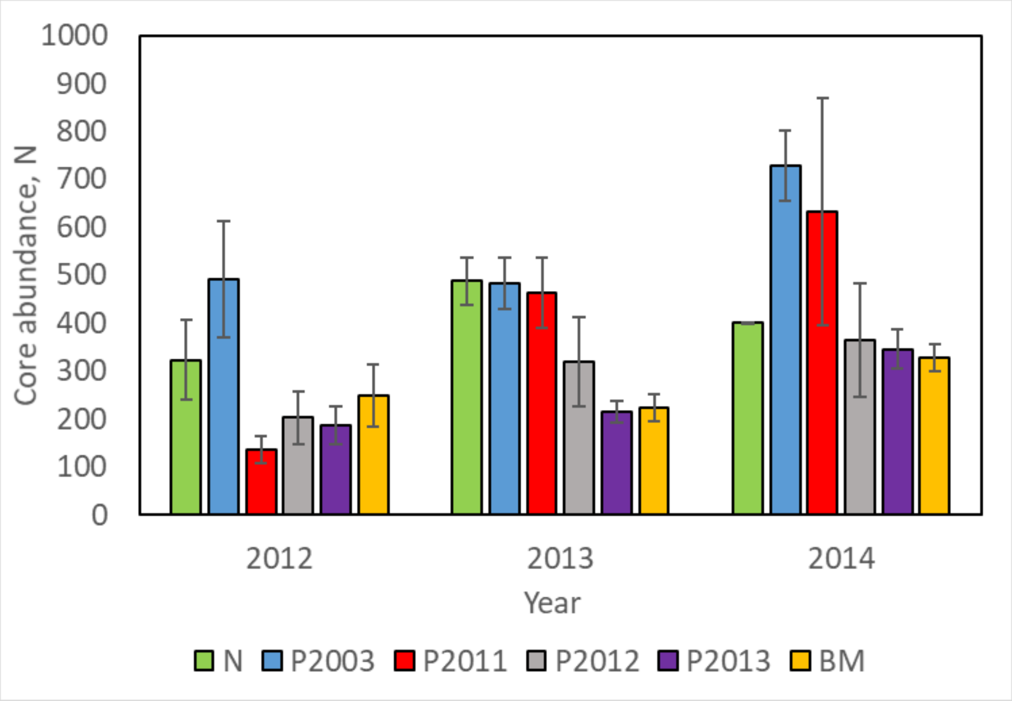
The presence of insects at the natural site also accounted for some of the dissimilarity with the planted sites, however the abundance of oligochaetes, in particular *Enchytraeidae* and *Tubificoides pseudogaster* agg. were the most consistent and dominant reason for the dissimilarity observed with nematode abundance also contributing notably to the dissimilarities observed. The dissimilarities observed between the planted sites were generally due to differences in the abundance of oligochaetes and the polychaete, *Pygospio elegans*.

4.4.1.2 Univariate Analyses: Abundance and species richness

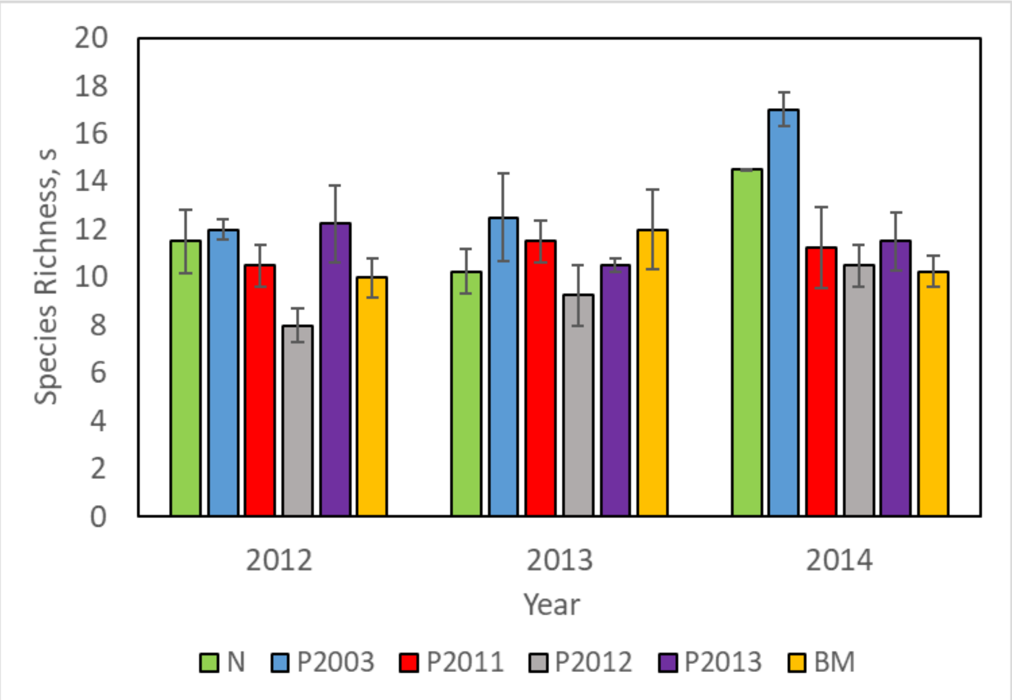
Mean abundance and species richness per site were calculated for each year (Figure 4.5) and 2-way ANOVA completed to determine if differences existed. Neither abundance or species richness were found to have significant interactions (Table 4.4).

Mean abundance was found to be significant for site and year. *Post hoc* Tukey tests revealed that site 2003 was significantly different from sites 2012, 2013 and the bare mud. Sites 2012, 2013 and the bare mud always had lower mean abundance values than the natural and 2003 sites. Site 2011 have the most variable abundance values.

Mean species richness was found to be significant for year but not site. Although site was not significant, the species richness at sites 2012, 2013 and the bare mud were the lowest in all years as with abundance.



a



b

Figure 4.5: Mean a) core abundance, N and b) species richness, S for all sites (represented by colour) sampled in March 2012, 2013 and 2014. Error bars represent standard error (n = 4).

Table 4.4: Summary results 2-way ANOVA with interaction comparing species richness and total core abundance across all sites (fixed) and years (random) with interaction. Bold text indicates a significant result.

		Site	Year	Site*Year	Residual
	DF	5	2	10	54
S	F statistic	3.26	4.41	1.69	
	p - value	0.059	**0.016**	0.103	
N	F statistic	4.72	8.19	1.23	
	p - value	**0.02**	**0.001**	0.28	

4.4.2 Seasonal Time series

4.4.2.1 Multivariate Analyses: Community assemblage comparison

The nMDS plot visualised for all cores sampled in March, July and November 2012 and March 2013 (Figure 4.6) had no distinct groupings between sites with overlap between points for all sites when considering site alone. Within this large group, the bare mud site remained the most distinct from all sites, with the sites planted in 2011 and 2013 grouped the furthest from the bare mud and other sites situated in between. Groupings by month were apparent, with July appearing the most distinct and having the smallest spread within site. March samples were visualised the furthest from July with November situated in between, however some sites had considerable overlap between November and both March cores. When considering the effect of month and site together, clear variation between clusters was observed, with July demonstrating the lowest variation and both March samples, the highest. In July, three clusters consisting of sites 2011 and 2013, sites 2003, 2012 and natural and finally the bare mud were visible. Whilst these groupings were visible in other months they were less distinct with some overlap between the all planted sites.

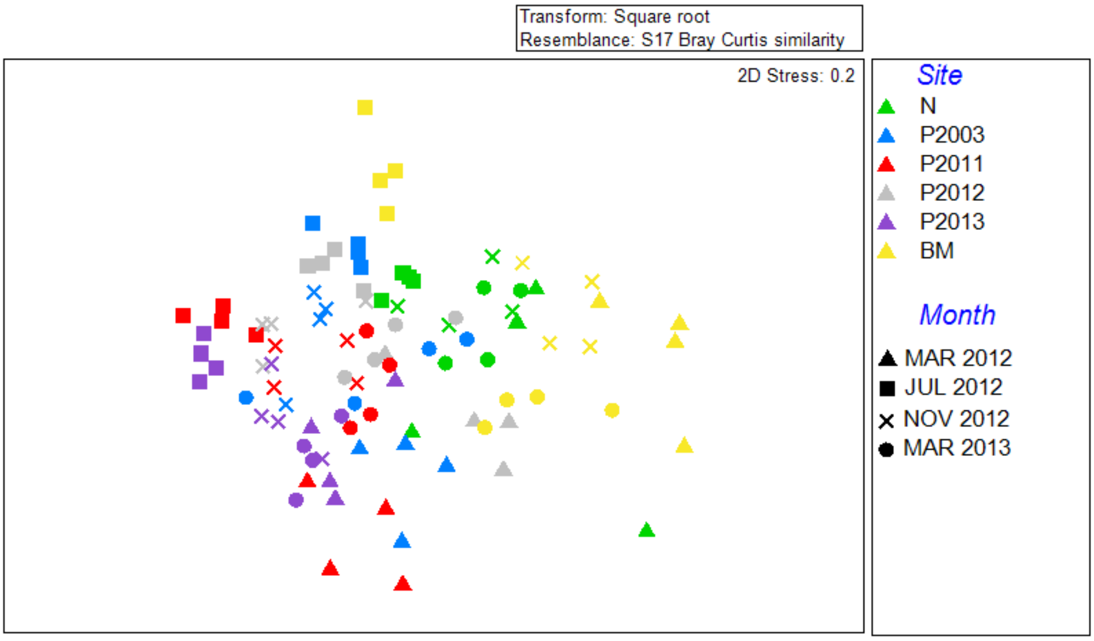


Figure 4.6: Non-metric multidimensional scaling (nMDS) plot of macrofaunal assemblages based on square root transformed abundance data from sites (represented by colour) within the Eden Estuary sampled over a 13-month period (represented by symbol). Sites included natural salt marsh stands (N), salt marsh planted in 2003 (P2003), 2011 (P2011), 2012 (P2012) and 2013 (P2013), and a bare mudflat (BM).

PERMANOVA analysis revealed a significant interaction between site and month and significant main effects for month but not site (Table 4.5). This reflects the visualisation discussed for the nMDS plot (Figure 4.6). PERMDISP analysis was not significant for site, however it was significant for the interaction term and year (Table 4.5) indicating that variances may not be homogenous across years. Although PERMANOVA is known to be robust to violations of homogeneity, unlike the three-year data where the PERMDISP significance was borderline, the significance with this dataset was high. After examination of the distance from centroids and the nMDS plot it was decided that it was likely that the data did violate the assumption of homogeneity. ANOSIM, which is analogous to a non-parametric ANOVA as it uses ranks of dissimilarity rather than actual distances like PERMANOVA was employed.

ANOSIM analysis revealed a significant effect of site and year (Table 4.5); it is not possible to test for an interaction with ANOSIM. The R statistic which indicated a reliable difference in separation within groups for both main effects was present. Site had a higher R value indicating that the separation between groups was higher than for month (Table 4.5).

Table 4.5: Summary of PERMDISP, PERMANOVA and ANOSIM results for differences in macrofaunal community assemblage between all sites and months between March 2012 and March 2013. Bold text indicates a significant result.

Test		Source of variation		
		Site*Month	**Site**	**Month**
PERMDISP	df	23, 72	5, 90	2, 92
	F	3.32	2.21	8.43
	P(perm)	**0.0110**	0.1030	**0.0010**
PERMANOVA	df	15, 72	5, 72	3, 72
	Pseudo-F	7.10	19.20	2.98
	P(perm)	**0.0001**	**0.0001**	**0.0001**
ANOSIM	Global R	-	0.77	0.66
	Significance (%)	-	**0.01**	**0.01**

Pairwise test results for month (Table 4.6a) indicated that July was most distinct from all other months, with the highest distinction observed between July and March 2013, followed by March 2012. November had the highest similarity with July but was still considered to have a reliable difference between months. November was equally distinct from both March 2012 and 2013 with the same R value estimated indicating a reliable difference between the months. March 2012 and March 2013 unsurprisingly had the lowest R value indicating that they were the most alike of the four time points sampled, with the R value indicating that the differences were notable but not greatly distinct.

Pairwise test results for site (Table 4.6b) indicated that the bare mud site was the most reliably different from all other sites, having values exceeding r = 0.9 for all planted sites. Despite the R value (0.78) being lower when comparing bare mud with the natural site the difference was still considered reliable. The natural site also reliably differed from all planted sites, however the difference was more reliable with sites planted in 2011 and 2013 than with those planted in 2003 and 2012. The differences observed within the planted sites indicated that site 2003 reliably differed from all other planted sites with the most reliable difference occurring between sites 2003 and 2013. R values for site 2011 indicated that the differences with sites 2012 and 2013 were notable but not greatly distinct. The variance observed between site 2012 and 2013 was reliably different.

Table 4.6: Summary of ANOSIM pairwise R values for differences in macrofaunal community assemblage for a) month and b) site. Colour scale represents degree of separation between groups with red indicating perfect separation of groups (R = 1) and green indicating notable but not greatly distinct groups (R = 0.2).

a) Month	Mar-12	Jul-12	Nov-12
Jul-12	0.82		
Nov-12	0.59	0.72	
Mar-13	0.38	0.90	0.59

All R values significant at 0.01%

b) Site	N	P2003	P2011	P2012	P2013
P2003	0.65				
P2011	0.83	0.77			
P2012	0.63	0.68	0.39		
P2013	0.89	0.86	0.42	0.70	
BM	0.78	0.98	1.00	0.92	1.00

All R values significant at 0.01%

As with the three-year data, individual nMDS plots were visualised (Figure 4.7) and 1-way PERMANOVA tests performed (Table 4.7) for each year to enable a more informed comparison between sites.

The nMDS plots illustrated clustering between sites in all months, however the grouping was clearer in July and November than in March 2012 and 2013. The bare mud site was the most distinct site grouping in all months. The level of separation between the planted sites and the natural site varied between months. PERMANOVA tests for each month confirmed that site was significant for all months with PERMDISP indicating that no significant differences in heterogeneity between sites in any one month were significant. *Post hoc* pairwise tests (Table

4.8) were performed for all sites to compliment the nMDS visualisation of the community assemblage and directly compare the average similarity of the community between sites within any month.

March 2012 and 2013 both generally had lower levels of pairwise similarities than either July or November, with July having the highest pairwise similarity, which correlates with observed spread of points in the nMDS plots.

For all months, the bare mud site has the highest dissimilarity with all other sites. The bare mud site was significantly different from all sites in all months except for the natural site in March 2012 and sites planted in 2003 and 2011 in November. The natural site was significantly different from all planted sites in all months except for site 2012 in March 2012. As suggested in the three-year analysis, the insignificant pairwise results between the natural site with bare mud and site 2012 could be due to the higher dissimilarity observed at the natural site for this month.

Differences and significance in the pairwise similarities between the planted sites in March, July and November 2012 indicate that the oldest planted site, 2003 was significantly different from all other planted sites. During these months the youngest planted site was also always significantly different from the other planted sites. Differences and significance of pairwise similarities varied between time points for planted sites 2011 and 2012 with no obvious trends.

Table 4.7: Summary of PERMDISP and PERMANOVA results for the analysis of differences in macrofaunal community assemblage structure across sites. Tests were run separately for years*. Bold text indicates a significant result.*

Month	Test	df = 5, 18	Source of variation: Site	Residual
Mar-12	PERMDISP	F	0.77	
		P(perm)	0.83	
	PERMANOVA	MS	3490.2	614.5
		Pseudo-F	5.68	
		P(perm)	**0.0001**	
Jul-12	PERMDISP	F	2.54	
		P(perm)	0.14	
	PERMANOVA	MS	2433.9	184.32
		Pseudo-F	13.205	
		P(perm)	**0.0001**	
Nov-12	PERMDISP	F	3.59	
		P(perm)	0.06	
	PERMANOVA	MS	3011.4	315.77
		Pseudo-F	9.5366	
		P(perm)	**0.0001**	
Mar-13	PERMDISP	F	0.72	3.6
		P(perm)	0.79	
	PERMANOVA	MS	2035.3	345.5
		Pseudo-F	5.89	
		P(perm)	**0.0001**	

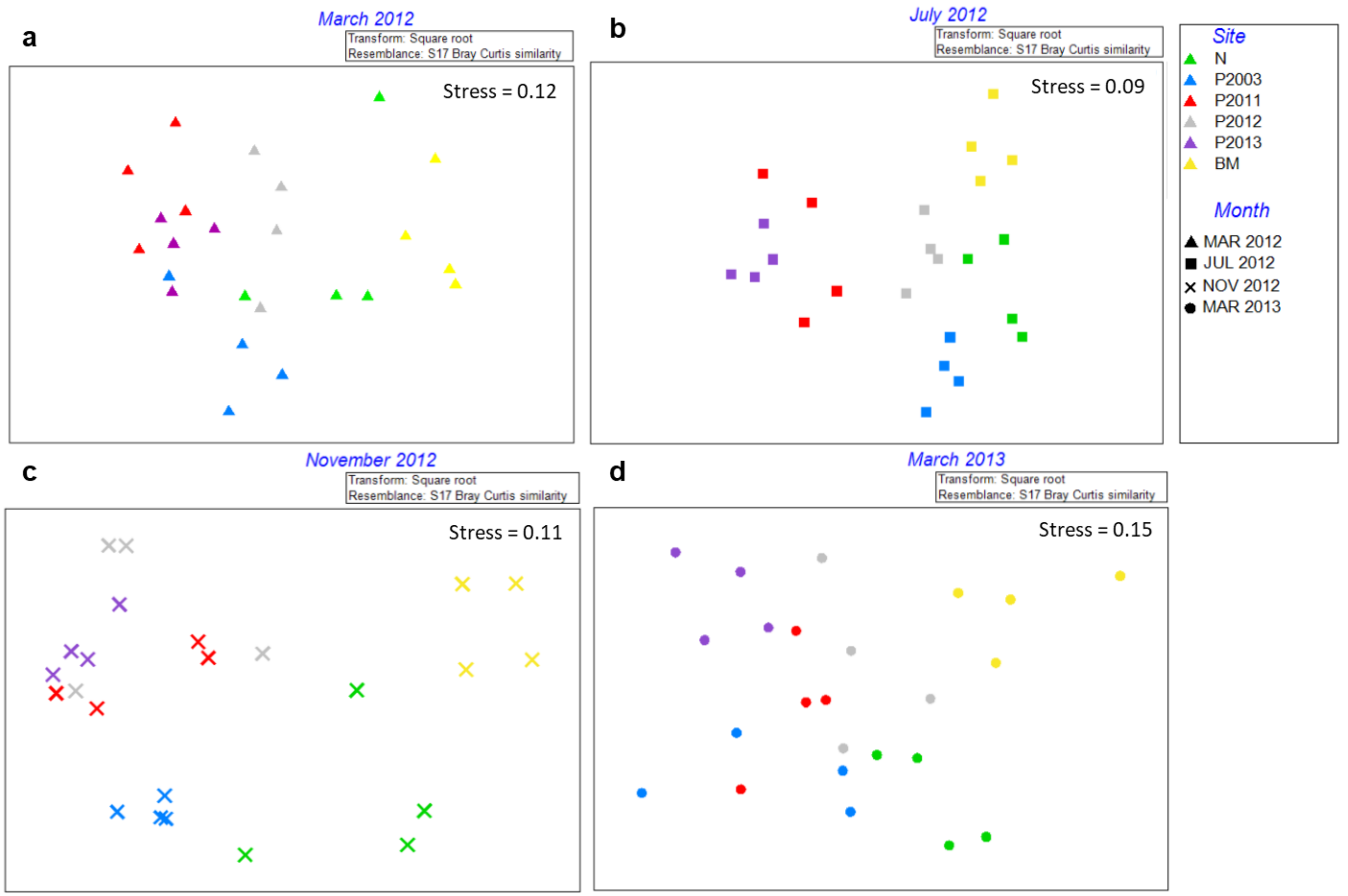


Figure 4.7: Non-metric multidimensional scaling (nMDS) plots of macrofaunal assemblages based on square root transformed abundance data for sites (represented by colour) natural salt marsh stands (N), salt marsh planted in 2003 (P2003), 2011 (P2011), 2012 (P2012) and 2013 (P2013), and a bare mudflat (BM). Individual plots for each time point a) March 2012, b) March 2013, and c) March 2013.

Table 4.8: P*ost hoc* pairwise comparisons of macrofaunal community assemblage using PERMANOVA for all sites using seasonal data. Tests were run separately for months. Similarity: average similarity within/between sites, the colour gradient from green to red represents high to low similarity. p(MC) is the probability using the Monte Carlo method; bold text indicates a significant result.

Month	Site	Natural Stand		P2003		P2011		P2012		P2013		Bare Mudflat
		Similarity	p(MC)	Similarity	p(MC)	Similarity	p(MC)	Similarity	p(MC)	Similarity	p(MC)	Similarity
Mar-12	Natural Stand	57.9										
	P2003	51.9	**0.046**	66.8								
	P2011	43.4	**0.009**	50.7	**0.017**	67.7						
	P2012	55.2	0.093	54.2	**0.028**	57.1	**0.030**	66.5				
	P2013	51.2	**0.018**	55.7	**0.021**	64.3	0.064	59.6	**0.030**	72.4		
	Bare Mudflat	53.9	0.056	37.7	**0.002**	30.1	**0.001**	48.7	**0.008**	35.6	**0.001**	68.6
Jul-12	Natural Stand	82.4										
	P2003	71.8	**0.003**	85.7								
	P2011	57.0	**0.002**	58.6	**0.002**	76.0						
	P2012	74.4	**0.012**	70.9	**0.003**	68.5	**0.084**	82.0				
	P2013	53.1	**0.000**	55.0	**0.000**	74.3	**0.001**	62.2	**0.008**	81.0		
	Bare Mudflat	65.8	**0.004**	53.7	**0.013**	54.7	**0.001**	72.3	**0.000**	49.1	**0.002**	82.4
Nov-12	Natural Stand	70.1										
	P2003	60.6	**0.006**	84.7								
	P2011	55.8	**0.008**	66.1	**0.007**	72.4						
	P2012	52.3	**0.004**	61.2	**0.004**	71.8	0.146	73.2				
	P2013	50.4	**0.002**	64.2	**0.001**	72.8	**0.001**	70.8	**0.001**	78.3		
	Bare Mudflat	59.2	**0.008**	44.3	0.306	46.6	0.054	44.5	**0.000**	39.4	**0.002**	76.0
Mar-13	Natural Stand	77.4										
	P2003	63.2	**0.023**	70.1								
	P2011	66.4	**0.015**	66.8	0.066	75.5						
	P2012	66.0	**0.023**	66.0	0.070	71.1	0.128	72.8				
	P2013	53.8	**0.002**	60.9	**0.011**	70.8	0.065	63.3	**0.010**	74.7		
	Bare Mudflat	59.3	**0.009**	52.8	**0.003**	57.6	**0.002**	59.9	**0.004**	52.5	**0.002**	76.0

SIMPER analysis was used to examine the taxa responsible for the dissimilarities in community assemblage between the sites and months identified using ANOSIM and nMDS. The oligochaetes, *Enchytraeidae* and *Tubificoides pseudogaster* agg. were the most consistent and dominant reason for the dissimilarity between sites and months. In general, both oligochaetes were more abundant in March 2012 and 2013 than in November and less abundant than in July. Generally, the natural site had higher abundances in the oligochaetes than all other sites, with the sites planted in 2003 having higher abundances than the other planted sites. In general, the bare mud site had the lowest abundance of all sites.

In July, a greater number of species contributed to the dissimilarities present between sites with the crustacea, *Corophium volutator*, and polychaetes *Pygospio elegans, Hediste diversicolor* and *Etone longa* and gastropod *Hydrobia ulvae* also being important contributors to the dissimilarities between community assemblage between sites. A higher abundance of *E. longa* were generally observed at the sites planted between 2011 and 2013 and a higher abundance of *P. elegans* and *C. volutator* and *H. ulvae* at all planted sites compared with natural and bare mud sites. In November the number of species contributing to the dissimilarity between sites was the smallest with *P.elegans* being the only taxa to consistently contribute to the dissimilarities between sites. In November *P. elegans had* a higher abundance at the planted sites than the natural or bare mud sites. In March 2012 and 2013 a lower abundance of *C. volutator* were present than in July and November with July also having a higher *H. ulvae* abundance.

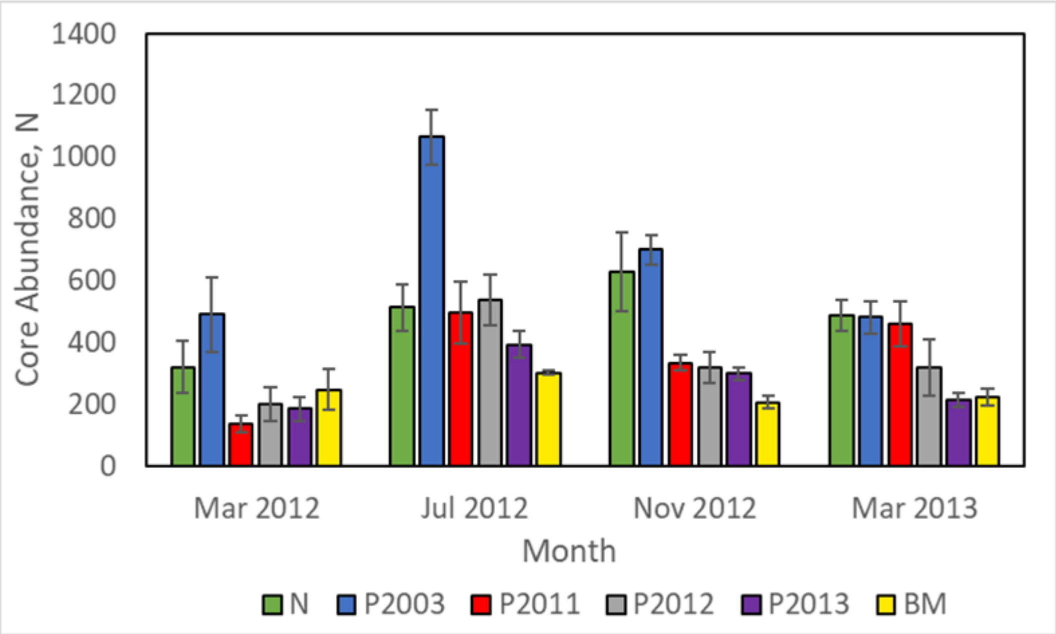
4.4.2.2 Univariate Analyses: Abundance and species richness

Mean abundance and species richness per site were calculated for each month (Figure 4.8) and 2-way ANOVA completed to determine if significant differences existed. Abundance and species richness were found to have significant interactions (Table 4.9) indicating that the relationship between both variables is complex and that unsurprisingly seasonal trends exist alongside variations between sites. This is reflected by mean abundance and species richness (Figure

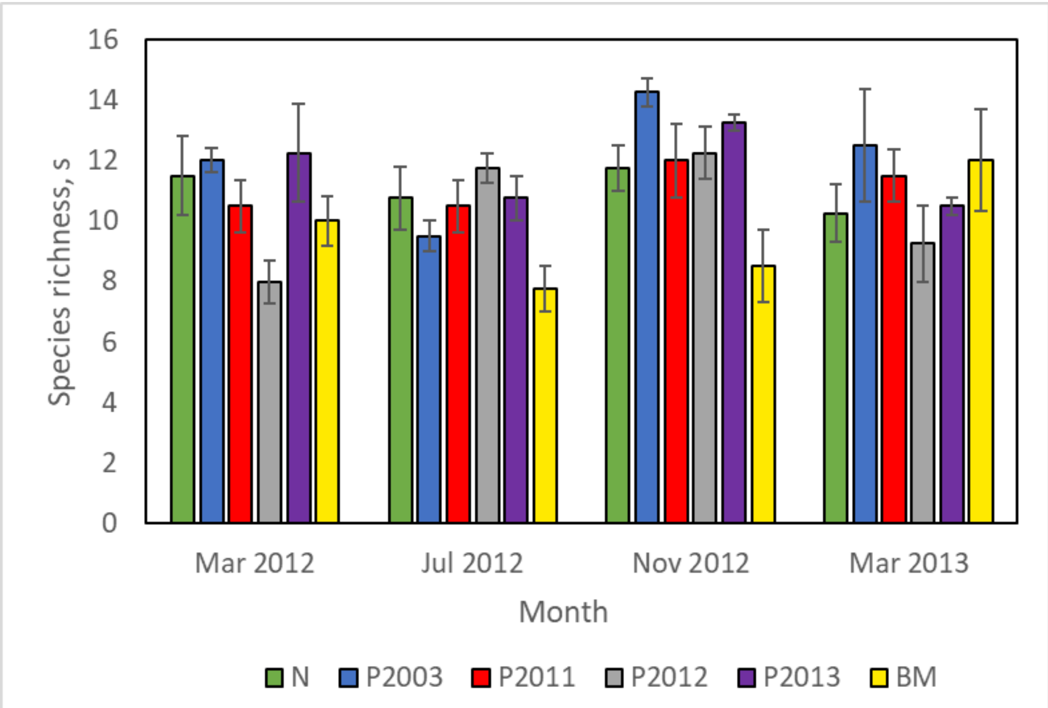
4.8) which do not illustrate a consistent trend when considering month and individual site alone. Grouping the sites enables some general patterns to be noted with the sites planted between 2011 and 2013 and the bare mud site always having a lower mean core abundance than the oldest planted site (2003) and the natural site. The oldest planted site (2003) has comparable or higher mean core abundance than all other sites, including the natural across all months. With the exception of the natural site, July had the highest mean core abundance of all months for each site. The highest mean species richness was observed for all sites except the bare mud in November.

Table 4.9: Summary results 2-way ANOVA with interaction comparing species richness and total core abundance across all sites (fixed) and months (random) with interaction. Bold text indicates a significant result.

		Site	Month	Site*Month	Residual
	DF	5	3	15	72
N	F statistic	8.64	19.33	2.77	
	p value	**0.002**	**0.001**	**0.01**	
S	F statistic	1.56	3.57	2.14	
	p value	0.238	**0.02**	**0.015**	



a)



b)

Figure 4.8: Mean a) core abundance, N and b) species richness, S for all sites (represented by colour) sampled in March, July, November 2012, and March 2013. Error bars represent standard error (n = 4).

4.5 Discussion

Interpreting the changes in community composition was complex due to the presence of interactions between time and site. This illustrates the need for effective and meaningful monitoring of restoration projects to take place over a period of time and not as an isolated time point in order to account for any temporal variability. Despite this natural complexity some general trends were observed.

4.5.1 Three-year Data set

4.5.1.1 Community Assemblage Comparison

The bare mud and natural sites, which were geographically more separate from the planted sites, were generally found to have distinctly different community assemblages to those of the planted sites. The bare mud site was the most distinct and always had the least similarity, including when compared to the youngest planted site prior to it being planted. This strongly suggests that the different planted sites and the reference sites had differing community assemblages even before planting. The sediment texture analysis in chapter 3 (section 3.4.3.2) identified the reference sites as having a finer muddy-sand sediment compared to the planted sites which had a coarser sandy sediment. Further analysis revealed that the muddy sand texture also had different sediment properties including a higher organic and water content. The sediment type is known to affect community composition and is likely a reason from the difference in community assemblage between the two locations.

Whilst the difference due to location should not be ignored it is also important to note that the natural salt marsh community assemblage almost always had a higher similarity to the planted sites that to the bare mudflat site, suggesting that the planted sites are developing a community more like the natural salt marsh stand. Other studies have found that when biodiversity measures such as Shannon index are comparable between restored sites, the community composition still differs (Swamy *et al.*, 2002; Curado *et al.*, 2014). A different community composition could lead to a different suite of EF, or the same EF where different taxa fulfil a similar role at different sites (Zedler and Callaway, 1999; Lotze *et al.*, 2011; UK National Ecosystem Assessment, 2011b).

When comparing the similarities of only the community assemblages of the planted sites an influence of the proximity of the planted site to natural salt marsh was apparent. The oldest planted site (2003) and 2012 sites were both adjacent to the eroded *Pucinella* salt marsh, site 2011 was approximately 100 – 150m away from the degraded salt marsh and the youngest site (2013) was the furthest at approximately 200 – 250m (Figure 4.9). Despite site 2012 being planted a year after site 2011 it generally had a higher similarity in community assemblage compared to site 2003. The youngest planted site had the least similar community assemblage to the oldest planted site, however, it was also the furthest site from the degraded marsh. Subsequently, it was not possible to determine whether the dissimilarity in community assemblage was due to distance from a natural marsh or the time since planting. It is perhaps unsurprising that proximity to a natural salt marsh influences the speed with which macrofaunal community assemblage attains comparable similarity as studies have already established that this influences the development trajectory of plant species since seed and propagule distribution is largely dependent on the tidal exchange (Young, Petersen and Clary, 2005; Adnitt *et al.*, 2007; Morzaria-Luna and Zedler, 2007). Nordstrom et al. (2014) describes this as the ‘build it and they will come’ idea.

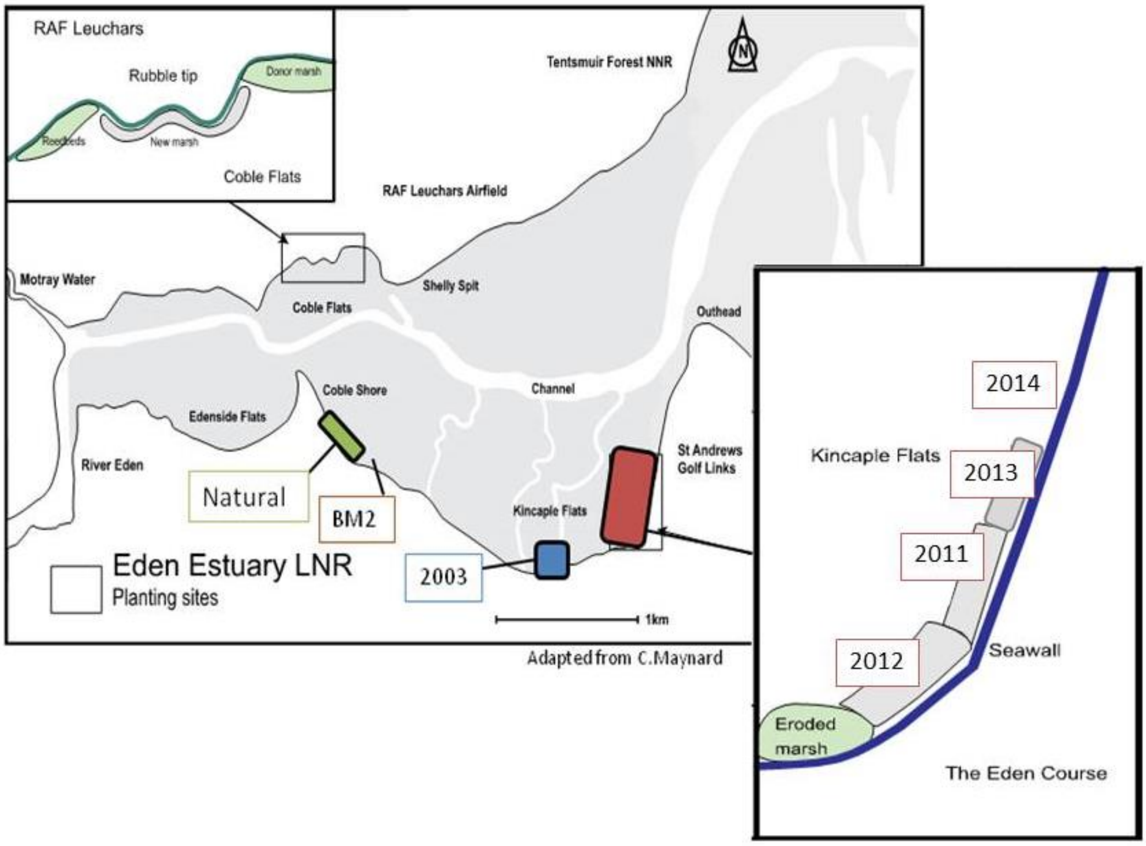


Figure 4.9: The location of each planted site on the south shore of the Eden Estuary, the natural donor stand and bare mud sites (BM2). Figure adapted from Maynard 2014.

4.5.1.2 Abundance and species richness

Core abundance appears to be less influences by the proximity to the natural salt marsh with the lowest abundances always being present in the youngest sites (2012 and 2013) and the bare mud site and the highest in the oldest planted site (2003) and the natural site. Site 2011 appears to be more volatile with some years being more comparable to the natural site, and other years more comparable to the mudflat. This suggests that equivalence in abundance is attained within 4 - 9 years of planting. Although not significant, the same trend was observed for species richness with the youngest sites and the bare mud site always having lower species richness than the natural and bare mud. The difference in species richness between sites was insignificant suggesting that comparable species richness is attained in a shorter time than abundance, 2 – 3 years. The oldest planted site had the highest species richness and abundance in some years, exceeding that of the natural site; this pattern was also noted by Curado et al. (2014) and Swamy et al. (2002).

4.5.2 Seasonal Time series

4.5.2.1 Community Assemblage Comparison

As with the three-year data, the bare mud had the most distinct community assemblage of all the sites across all months and the natural site had the highest similarity in community assemblage of all the sites. Site 2013, which wasn't planted until the last sampling point in this data set, remained distinct from the bare mud site during all months. This supports the geographical location having an influence on the community assemblage due to differences in the sediment composition and type.

Again, the natural site also differed from the planted sites and the bare mud site, with the community assemblage having a higher similarity with the planted sites despite the difference in location and sediment type. Once again, the age of the planted site and the proximity to natural salt marsh appeared to be influential with the site planted in 2012 having a more comparable community assemblage to the oldest planted site and the natural site than the site planted a year earlier in 2011. As with the three-year data this suggests that the benthic macrofaunal community at sites closer to a natural salt marsh achieve equivalency faster which should be considered when planning future restoration work.

Clear differences were observed between the composition, the variability and the within site grouping of the community composition over the months/seasons. March 2012 and 2013 had the highest similarity of the months which is unsurprising, however the community assemblage was still notably different which could be attributed to changes in abiotic factor such as temperature. March 2013 was colder (Table 4.10) and stormier (pers. comm. Maynard) than March 2012. The observed annual variation supports the argument for long term monitoring to assess the success of a restoration project (Young, Petersen and Clary, 2005; Adnitt *et al.*, 2007; Rey Benayas *et al.*, 2009; Zhao *et al.*, 2016).

Table 4.10: Mean temperature for months when macrofauna were sampled. Air temperatures were recorded at a minimum height of 1.25 m above ground in a louvered white screen. The grass minimum temperature is the lowest temperature reached overnight by a thermometer touching the tips of short grass. The soil depth temperature was recoded at a depth of 10 cm. Data recorded at Leuchars MET Station (https://www.midas-data.org.uk/).

Year	Month	Mean Monthly Temperature (˚C)			
		Max Air	Min Air	Grass	Soil 10cm depth
2012	March	10.8	5	-1.2	8.2
2012	July	15.8	11.5	8.1	16.1
2012	November	7.7	2.7	-2	4.2
2013	March	4.6	0.5	-4.2	2.9
2014	March	9	4.6	-0.6	6.3

July had the most distinct clusters and the highest within site similarity in community assemblage of all months. November community assemblages had a higher similarity to July than to either March. If considered alone, a higher attainment of equivalence in community assemblage was recorded in July between sites 2003 and 2012 when compared to the natural site than in any other month with 2012 appearing to have achieved comparable levels to 2003. The community at site 2011 had a lower level of equivalence with the natural site than 2012, once again supporting the positive effect that proximity to natural salt marsh has on restoring the benthic macrofaunal. This has implications when assessing whether restoration has been successful as the season that monitoring occurs has an impact on the outcomes which can lead to ambiguity as to when a restored or created site can be considered to have attained equivalence with a natural reference site. In this instance, if sampling had only occurred in July we might assume a higher level of equivalence had been reached than if sampling had only occurred in March. Consequently, where possibly seasonal monitoring should take place in order to truly understand whether equivalence in macrofaunal community assemblage has been achieved.

4.5.2.2 Abundance and species richness

The univariate measures used for biodiversity, core abundance and species richness, appear to vary little in the first few years after planting with sites 2012 and 2013 having comparable values, particularly in July and November. Other studies have found that the initial colonisation by invertebrates (above and below ground) tends to be rapid, achieving an “intermediate equivalence”. However, attaining full equivalence takes a longer period (Swamy *et al.*, 2002; Moreno-Mateos *et al.*, 2012; Curado *et al.*, 2014). The oldest planted site often attained levels of abundance and to a lesser degree species richness greater than that of the natural site across all months; this has also been observed in other planted sites (Levin, Talley and Thayer, 1996; Curado *et al.*, 2014).

The variability in the univariate measures (species richness and abundance) appears to be less between months than that observed in multivariate analysis (community assemblage comparisons). It is generally accepted that multivariate community assemblage analyses, such as those possible in PRIMER, provide a greater level of information and flexibility than univariate analyses such as species richness (Anderson, Gorley and Clarke, 2008). Whilst species richness has been proven to demonstrate a good relationship between biodiversity and EF (Cardinale *et al.*, 2012; Balvanera *et al.*, 2014), consideration should be given to the incorporation of more multivariate analyses when assessing restoration projects. The greater sensitivity to differences in biodiversity at the community level, such as those found in this research, suggest that it may provide a more accurate assessment of whether EF is restored.

4.5.3 Community Composition

For both datasets the main taxa responsible for the dissimilarities between sites and over time were the oligochaetes, *Enchytraeidae* and *T. pseudogaster* agg. *C. volutator*, *H. ulvae,* nematodes and *P. elegans* also contributed substantially to the differences at some time points. Curado et al. (2014) reported high abundances of oligochaetes at their created salt marsh sites and identified them as a key taxon. The identification of key species in assessing the recovery trajectory of restored or created sites could enable a speedier, less time-consuming and less destructive method for evaluating the success of restoration projects. A meta-analysis comparing different biodiversity measures found the use of population level monitoring of an individual species did not always demonstrate a good relationship to EF (Balvanera *et al.*, 2006) and therefore could be misleading when assessing the success of restoration projects. In addition, it has been noted that in some systems key species can be uncommon until specific environmental conditions occur after which their abundance may change dramatically (e.g. seasonal temperature changes, excessive nutrient supply) (TEEB, 2010). The less abundant a species is, the greater the sampling effort required. This would impact both the effort required to sample and destructive impact on the restoration. These considerations illustrate the need for continued research into the role of individual species within an ecosystem if a representative and key species is to be found for assessing the success of salt marsh restoration.

4.6 Conclusion

- Benthic macrofaunal species richness comparable to a natural salt marsh (reference site) was attained 2-3 years after planting.
- Benthic macrofaunal core abundance comparable to a natural salt marsh (reference site) was attained 4 – 9 years after planting.
- Annual and seasonal variability were present in the data and illustrate the importance of long-term monitoring that includes sampling in different seasons when assessing the success of a restoration project.
- The restoration of benthic macrofaunal community assemblage is influenced by the proximity of the planted site to a natural salt marsh site. Sites nearer to natural salt marsh achieved a higher similarity in community assemblage than those further away. This is likely due to the spread of taxa being largely dependent on the movement of water (tides).
- The sediment characteristics and the climate influenced the community composition present at a site. This made direct comparisons between the sites impossible with the current data set due to cumulative confounding factors.

Chapter 5: Valuation of Coastal Defences in the Eden Estuary, Fife

5.1 Introduction

Concern regarding coastal flooding and erosion have increased worldwide over the past decades. Increases in storm frequency coupled with sea level rise, both associated with climate change, are predicted to leave coastal areas more vulnerable to flooding and erosion in the future (Pethick, 2001; Simas, Nunes and Ferreira, 2001; Jongman, Ward and Aerts, 2012; Donovan *et al.*, 2013; Defra, 2015). The threat from coastal flooding and erosion is identified in the UK Marine Policy as a climate change impact that will require careful adaptation in terms of ensuring that proposed new developments are resilient over their lifetime (HM Government, 2011). It is also prioritised in Defra's Climate Change Risk Assessment as an issue requiring immediate action (Defra, 2012, 2017). In addition to direct damage to properties and infrastructure including road and rail links, energy substations and agricultural land, indirect losses from flooding include disruption to business operation, injury and reduced health.

In Scotland, a National Flood Risk Assessment, Maps and Management Strategies and Local Management Plans have been produced to identify and focus mitigation in the areas with the greatest risk of flooding (CREW, 2012; SEPA, 2016). The Eden Estuary is part of the Tay Estuary and Montrose Basin Local Plan (Angus Council, 2016) which estimates that 2.5% of residential and 9% of non-residential properties, totalling 5200 properties, are currently at risk from a 1 in 200 year coastal flood. Estimated average damages from coastal flooding are £5.3 million per year in this region (Angus Council, 2016). The cost and extent of damage is only likely to increase given the predicted increases in storm frequency and sea level rise (CREW, 2012; SEPA, 2015b). Increasing our ability to manage flood risk is essential to reduce the extensive economic costs caused through the damage, both direct and indirect, that flooding causes.

Installing and maintaining coastal defences is costly. Historically, hard engineering methods, such as sea walls and groynes, were used to defend the coast, reducing the risk of flooding. The high cost associated with installing and maintaining hard defences and our improved understanding of how their use often results in the displacement of flood risk further along the coast has led to greater use of natural ecosystem based soft engineering methods often combined with some hard engineering (Defra, 2009; CREW, 2012; The Royal Society, 2014; SEPA, 2015b). Soft engineering, such as beach replenishment and the restoration of sand dunes and salt marshes, work with natural processes offering a more economically sustainable approach to defending the coast with little to no maintenance costs. (French, 2004; CREW, 2012; Foster *et al.*, 2013; Temmerman *et al.*, 2013; Narayan *et al.*, 2016). A disadvantage of solely using soft engineered techniques is the time it takes for the defence to become effective, as unlike hard engineered techniques there is a time lag before recently created natural defences become effective flood defences. This factor combined with the lack of public confidence in the ability of natural flood defences to be effective has led to combined defences, which implement soft and hard techniques, becoming increasingly utilised (Defra, 2009; Mangi *et al.*, 2011; The Royal Society, 2014; Barbier, 2016).

In Scotland, the Scottish Environment Protection Agency (SEPA) have overall responsibility for assessing and implementing a flood risk management strategy, however this is delegated to local authorities and other relevant public bodies to implement at a more local level (SEPA, 2016). Public funds are limited and where defences are installed they are often funded privately or through the formation of partnerships between local authorities and stakeholders. Decisions relating to coastal defences are often contentious within communities at risk from flooding with the local authority and the SEPA needing to consider economic, social, environmental and physical factors when determining the optimum use of the limited resources available. When making decisions, the ability to weigh up the actual cost of installing defences, any estimates of the value of the benefits and the perceived value that the public place on them can assist decision makers in determining whether to proceed with a project and/or selecting the best management option available (Defra, 2007; Hanley and Barbier, 2009; TEEB, 2010; UKNEA, 2014).

The costs of installing and maintaining defences can be calculated by potential contractors completing the work. Quantifying the benefits provided by coastal flood defences is more challenging due to the inability of traditional markets to value public goods. Methods used to value non-market benefits that have been applied to natural coastal flood defences (including salt marshes) include the cost based, revealed preference and stated preference approaches (see section 2.2 for an overview of valuation methods).

5.2 Aim of Chapter

The increasing risk of coastal flooding and erosion is an ongoing concern within the Eden estuary. As discussed earlier, large areas of the coastline are at risk from flooding, with damages being costly (SEPA, 2015a; Angus Council, 2016). Decisions relating to the estuary are made by the Management Committee which consists of representatives from the local council, Scottish Natural Heritage (SNH) and stakeholders, including surrounding land owners and interested groups. With approximately 60% of the coastline being protected using hard engineering, mostly sea walls, which are costly to maintain, interest in the use of more sustainable and lower cost methods has increased. Over the past 15 years a partnership between many of the local land owners, the University of St Andrews, SNH and SEPA has developed. The aim of the partnership is to utilise soft engineering methods, including salt marsh and sand dune restoration, to provide a more economically sustainable flood defence scheme. Although coastal flood defence is not the only reason for this work, it is one of the key motivators for many of the funders.

The purpose of this chapter is to provide an insight into the local communities' views relating to coastal flood defences to better inform decision making in the region.

Aim 1: To understand whether the local community (north east Fife) has a preference for hard, soft or combined defences.

Aim 2: To understand whether the local community has a preference for the type of land that should be protected: e.g. private property, golf fairways or farm land.

Aim 3: To estimate the local communities' willingness to pay for coastal flood defences.

5.3 Review of Methods Used to Value Coastal Flood Defence

Cost based approaches, including the avoided cost method and replacement cost method, have been used to infer the value of natural coastal flood defences (Figure 5.1; King & Lester 1995; Mangi et al. 2011; Narayan et al. 2016; Brander et al. 2006). The avoided cost method evaluates the costs that would be incurred in the absence of an ecosystem service such as coastal flood defence in terms of damage to property, infrastructure and livelihoods caused by the flooding. The replacement costs method estimates the cost of replacing the ecosystem service with an artificial means such as a sea wall (TEEB, 2010). In the context of coastal flood defences, these methods require a good understanding of the natural ecosystems' resilience as a coastal flood defence and how this compares to the hard engineered alternative. Scale models, and more recently field studies, have been used to quantify a salt marshes' ability to absorb wave energy and attenuate waves thereby acting as a natural coastal defence (Möller and Spencer, 2002; Möller, 2006; R. A. Feagin *et al.*, 2009; Möller *et al.*, 2014). This reduces the need for high sea walls or in some cases avoiding the need for any sea walls (King and Lester, 1995b; Mangi *et al.*, 2011).

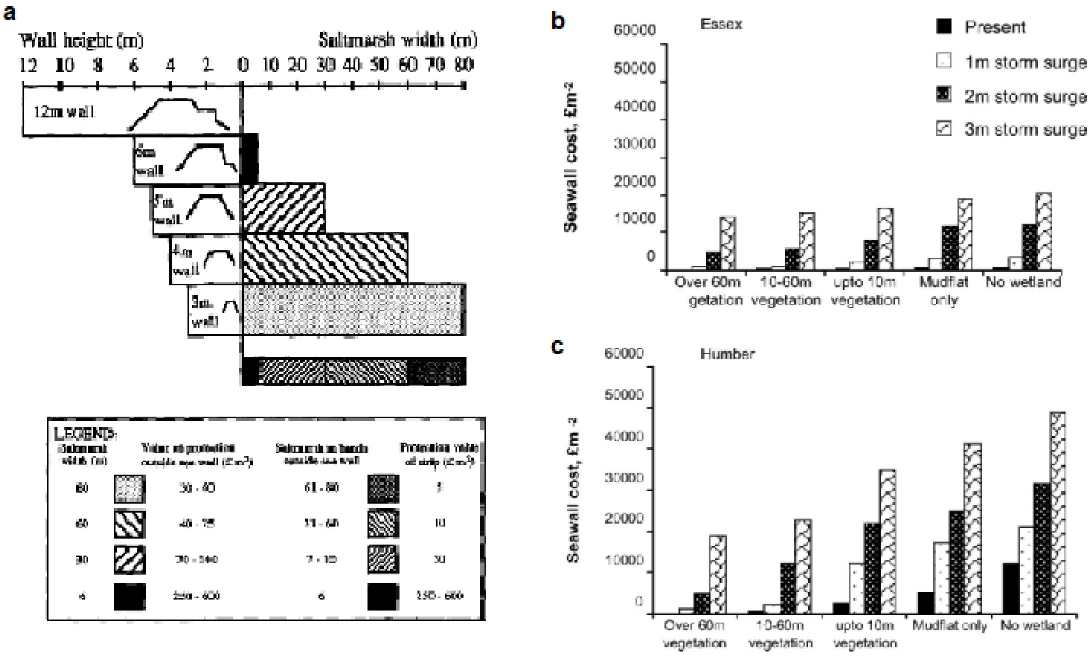


Figure 5.1: Examples of cost based approach estimates valuing coastal flood defences a) From King and Lester, 1995; Saving afforded by salt marsh on capital wall building costs; b) & c) From Mangi et al., 2011; seawall construction costs for b) Essex and c) Humber for five wetland width scenarios.

Cost based approaches do not incorporate public perception of the value of the benefits an ecosystem service provides. Engaging with the local community and understanding what their preferences are and the value they place on coastal flood defences can be very informative for decision makers, especially when public funds are being used to pay for the defences. The UK Government recognises the importance of this and its current policy includes extensive stakeholder consultation in the determination of any flood defence plans (Defra, 2009, 2015; SEPA, 2016). Two main categories of alternative non-market valuation methods exist: revealed preference and stated preference.

Revealed preference methods rely on using people’s behaviour to infer a value for a given environmental good from an existing market. Hedonic pricing, an example of revealed preference, utilises the price of houses and property to assess the value of a non- market good, such as coastal flood defence. Studies have found that houses located in areas prone to or at high risk of flooding have comparably lower value than equivalent houses located in areas not at risk of flooding (Brander, Florax and Vermaat, 2006; Mangi *et al.*, 2011).

Unlike revealed preference, which rely on existing markets which are related to an ecosystem service, stated preference methods simulate a market through the creation of hypothetical scenarios. Individuals are presented with a detailed description of one or more hypothetical scenarios which involve a change in one or more environmental goods. Individuals state which scenario is their preferred option taking into account any costs associated with a change. By modelling responses from many individuals, it is possible to estimate an individuals' preference for and their willingness to pay (WTP) for a change. The two main methods used are contingent valuation (CV) and choice experiments (CE).

CV asks respondents what they are willing to pay for a specific hypothetical environmental change. Modelling provides a value for the WTP for the specific environmental change proposed in the survey and can be used for all non-use values (Hanley and Barbier, 2009). CE can also be used to estimate all non-use values, however they have greater flexibility than CV as each hypothetical scenario consists of environmental attributes (Bateman *et al.*, 2011; Ozdemiroglu and Hails, 2016), for example, a beach may be described in terms of its water quality, size and cleanliness. Each attribute relating to the proposed environmental change can take on different levels, for example high, medium or low water quality. Respondents are presented with a set of scenarios which incorporate different levels of the attributes that contribute to the good in question, known as a choice set, and are asked to select their preferred option or rank the options available. By choosing between the scenarios, respondents make trade-offs between the levels of the attributes. Asking respondents to complete multiple questions with varying scenarios, the importance of each attribute and the preferred scenario can be recovered for the rankings of choices. Incorporating price/cost as one of the attributes within each scenario enables WTP for each attribute to be estimated alongside an estimate for scenarios which change multiple attributes simultaneously (Hanley and Barbier, 2009; Hensher, Rose and Greene, 2015). CE and the values they can provide are increasingly used to estimate environmental values and have proven to be a useful tool for policy makers in testing hypothetical scenarios (Bateman et al., 2002).

Many studies estimating the value of the environment in providing coastal flood protection have been completed using stated preference methods. The values are generally found to be higher than those produced by either cost based approaches (Rao *et al.*, 2015). A stated preference number of studies in the USA have been conducted to estimate WTP for wetland restoration and/ or coastal flood protection ((Woodward and Wui, 2001; Landry *et al.*, 2011; Petrolia and Kim, 2011; Petrolia, Interis and Hwang, 2014). The estimates have been varied, ranging from a WTP $189 to $237 per household per year (Petrolia, Interis and Hwang, 2014). An additional study only surveying Louisiana residents has estimated the WTP for flood risk reduction from coastal restoration through the introduction of levees to be $103 per household per year (Landry *et al.*, 2011) to $53 per household per year (Petrolia and Kim, 2011). In the UK CV studies have dominated over CE. Brouwer et al. (1999) calculated a mean WTP for wetland regeneration of £83.65 per household per year and Simpson & Hanley (2016) a mean WTP for managed realignment of £42.79 per household per year. Less conservative estimates were made by Mangi et al. (2011) and Defra & Environment Agency (2005) with WTP for the defensive role of coastal wetlands being £213 per household per year and £150 to £200 per household per year respectively. The high variability between these estimates can be partially explained by variations in the survey questions, time of sampling and survey design, however people clearly value wetlands as a form of coastal flood defence. Additional studies will improve our ability to quantify the value that people place on this ecosystem service.

5.4 Choice Experiment Design

The appropriate design of the choice experiment is crucial as poor design may lead to poor understanding of the question being asked of participants and inaccurate estimates of the respondents' value of the attributes included in the choice experiment (Hanley and Barbier, 2009; Hensher, Rose and Greene, 2015). The initial step requires us to determine the list of appropriate attributes and their alternatives and levels in order to answer the question being posed by the choice experiment. Choice cards are then designed, and the choice sets modelled.

5.4.1 Selection of Attributes

This research focusses on the value of salt marshes in the Eden Estuary. Salt marshes are known to provide a wide range of ecosystem services (section 1.5), however the importance placed on these will differ dependent of the location. To determine the most important ecosystem services and benefits provided by the salt marshes in the Eden estuary, face to face interviews with local stakeholders and managers were held. In addition to the importance currently placed on and reasons for supporting the restoration of salt marshes within the Eden, future plans or ideas for the development of the Eden estuary were discussed. The primary reason for this was to help in informing realistic management scenarios for the choice sets which is critical for experimental design (Hensher, Rose and Greene, 2015), however, from a practical point of view it was also important that any outcomes from this project would be considered useful. Two key benefits were identified through these interviews: coastal protection from flooding and erosion and habitat provisioning for birds that was important for recreation and tourism within the area. A list of potential attributes associated with these priorities were created for future management scenarios (Table 5.1).

Table 5.1: List of potential attributes associated with two ecosystem services compiled from interviews with stakeholders and managers of the Eden estuary

Ecosystem Service	Coastal Flood and Erosion Protection	Recreational Services
Attribute	Type of defences used	Improved footpaths
	Extent of defences	Improved signage
	Location of defences	Additional bird hide
	Type of properties protected	Visitor centre

Four focus groups containing 2 -4 residents local to the Eden Estuary were held to refine the attribute list (Table 5.1). Informal semi-structured interviews discussing the importance of the two ecosystem services and the attributes

(Table 5.1) and the general understanding and knowledge of these areas and management of the Eden estuary were discussed. Following this, it was decided to include only one of the ecosystem services in the survey as incorporating both services was considered too challenging to understand and would require extensive explanation making the overall survey too long. Coastal flood defence was chosen as a greater priority to the majority of the focus group participants.

The range for the price attribute levels was initially suggested to the focus groups based on the estimated costs of installing defences in the Eden estuary. These costs were presented to focus groups as the potential increase in council tax over a three-year period and discussed to assess whether they were appropriate and believable.

Data provided by existing land owners who have installed hard defences and Dr Claire Maynard (University of St Andrews), who is responsible for the salt marsh restoration work, were used to estimate the actual costs. The estimated cost of building a 3 m high gabion sea wall was £600 per metre of coastline (based on 2006 - 2008 values). The estimated cost of restoring a 4 m wide salt marsh was £100 per metre of coastline (based on 2010 – 2013 values). The cost of installing combined defences of a 2 m high gabion sea wall and 4 m wide salt marsh was calculated from these estimates to be £500 per metre of coastline. These values are likely to be underestimates as they only include the actual work and materials and not any additional costs such as planning applications.

These estimated values were scaled up to estimate the cost of installing defences along the entirety of coastline where coastal defences can be installed and a ‘hold the line’ policy is in place (approximately 17.5km) (Fife Council, 2011) and divided by the number of households in the target survey area. This provided a maximum cost of approximately £600 per household. This maximum cost was suggested to the focus groups in the form of council tax over a three-year period (maximum of £200 per year) and was considered to be acceptable.

The final selection of attributes (Table 5.2) for valuing coastal flood defence and their respective alternatives were chosen to enable the estimation of WTP for different types of coastal flood defences and how this varies dependent on the type of land being protected. An increase in council tax over a three-year period was incorporated as the cost attribute. This was selected as it was the most plausible method that respondents could understand and accept as a true possibility since local authorities are responsible for funding flood defence in Scotland. It should be noted however that given the current political circumstances in Scotland it is unlikely that a local council would increase their council tax as doing so would result in a detrimental loss of financial resources provided by the government and may be detrimental to the overall budget for the area.

When designing a CE, it is important to provide scenarios with attributes and levels that are realistic and believable by the respondents. Extensive research studies have shown failure to do this can lead to inaccurate parameter and WTP estimates (Hanley and Barbier, 2009; Hensher, Rose and Greene, 2015) Careful consideration and testing was included to ensure that the attributes used were well defined and applied to the 'real world' Eden estuary. The types, or alternatives for coastal protection were consistent with those already found in the Eden estuary. Hard defences, in this instance gabion sea walls, soft defences – salt marsh, and combined – sea wall and salt marsh were offered as alternatives. The type of land that was to be protected and the approximate percentages of coastline protected were representative of the proportions found in the Eden estuary.

Table 5.2: Attributes, their alternatives and levels used in choice experiment to value coastal flood defence in the Eden estuary. Where levels differed between the pilot and final survey the grey value represent the pilot survey levels.

Attribute	Attribute Description	Alternatives	Levels
Coastal Defence	The type of coastal defence used to protect the coast from flooding and erosion.	Hard/Sea Wall	Labelled alternatives
		Soft / Salt marsh	
		Combined / Sea wall and salt marsh	
		Status Quo/No Change	
Land Protected	The type and extent of land that will be protected by the coastal defences. *The alternates and maximum levels are representative of the proportions present in the Eden estuary.*	Property – residential and business	0%, 10%, 20%, 30%, 40%, 50%
		Farmland	0%, 5%, 10%, 15%, 20%, 25%
		Golf Courses	0%, 5%, 10%, 15%, 20%, 25%
Cost	Increase in council tax per household over a 3 yr period.	Council Tax	£120, £225, £360, £525, £675, £900
			£120, £216, £312, £408, £504, £600

5.4.2 Sample Area

The target area for sampling was north east Fife (Figure 5.2). The area has 17,543 households making up 10.3% of those present in Fife (The Scottish Government, 2013). The area has a mean council tax of £1,202.13 per household and a mean gross household income of £24,956.88 ± 4,925.44 per year (The Scottish Government, 2013). In 2006 5.54% of the properties in the area were considered to be at risk from flooding (The Scottish Government, 2013).

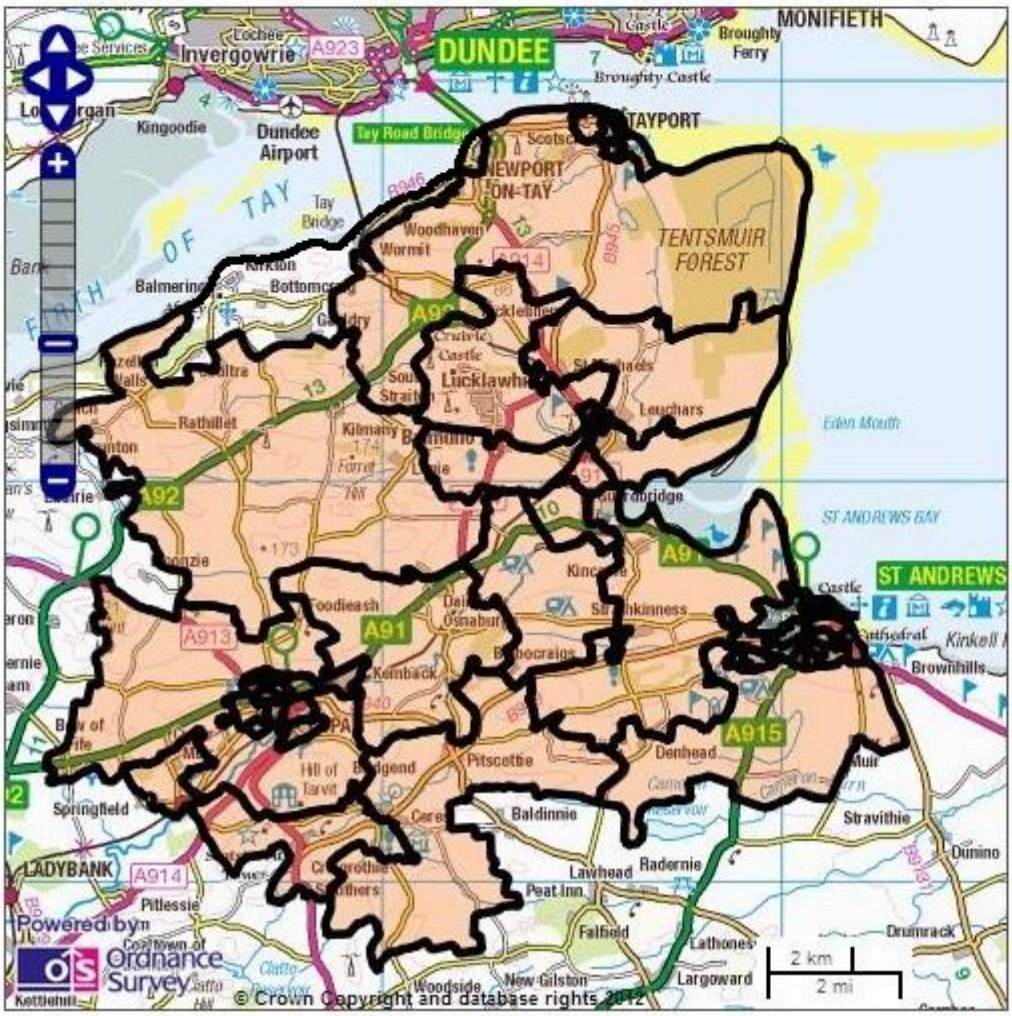


Figure 5.2: Target sample area of north east Fife used for choice experiment. Solid black lines represent SNS 2001 data zones. (Scottish Neighbourhood Statistics, 2013).

5.4.2.1 Survey Design

The survey consisted of four sections; background information and instructions on how to complete the survey, the choice cards, questions relating to the participants use of the Eden estuary and finally socio-demographic questions.

Studies have found that the level of information that is given to a respondent can be influential on the choices that the respondents make (Czajkowski *et al.*, 2016). It is important that this work is aimed at an audience with varying educational levels and that it is not assumed that the respondents have any prior knowledge of the topic of the survey (Hensher, Rose and Greene, 2015). The format that this information takes is commonly as written text and images read prior to completing the survey, although less commonly surveys have used vocal recordings and videos. A video was used for this survey as this was thought to be a more efficient and engaging method to communicate the information than the alternatives and consequently participants were more likely to retain more of the information provided. The full script can be found in appendix A.

The video began by discussing coastal flooding and erosion risk and placing it in the context of the Eden estuary. The attributes were all described in detail and the advantages and disadvantages of each of alternate forms of coastal defences were discussed. A brief overview of these was presented in a summary table (Figure 5.3). Once the attributes and their alternates and levels were explained an example of a choice card and an explanation of how to complete it was presented (Figure 5.4). Finally, a brief explanation asking respondents to consider the impact that any additional cost would place on the respondents' budget. Studies have found that this can counter potential bias due to the hypothetical market, particularly for those making higher payments (Carlsson, Frykblom and Johan Lagerkvist, 2005; Hanley and Barbier, 2009; Hensher, Rose and Greene, 2015).



Natural / Soft Defences e.g. saltmarsh planting	Manmade / Hard Defences e.g. sea wall	Combined Defences e.g. sea wall and saltmarsh
• Progressive protection (10 years)	• Immediate protection	• Some immediate protection which will increase over 10 years
• Sustainable	• Lifetime of 15-40	• Sea wall life extended
• No on going cost	• On going maintenance cost	• Maintenance costs less than for hard defences
• Blends well with the natural environment	• Dramatic change to the way the landscape looks	• Reduces height of sea wall required
• Additional habitat for wildlife	• No additional habitat for wildlife	• Additional habitat for wildlife

Figure 5.3: Advantages and disadvantages of the coastal defence alternates included in the choice experiment. It summarises the information provided in the information video for the coastal defence attribute.

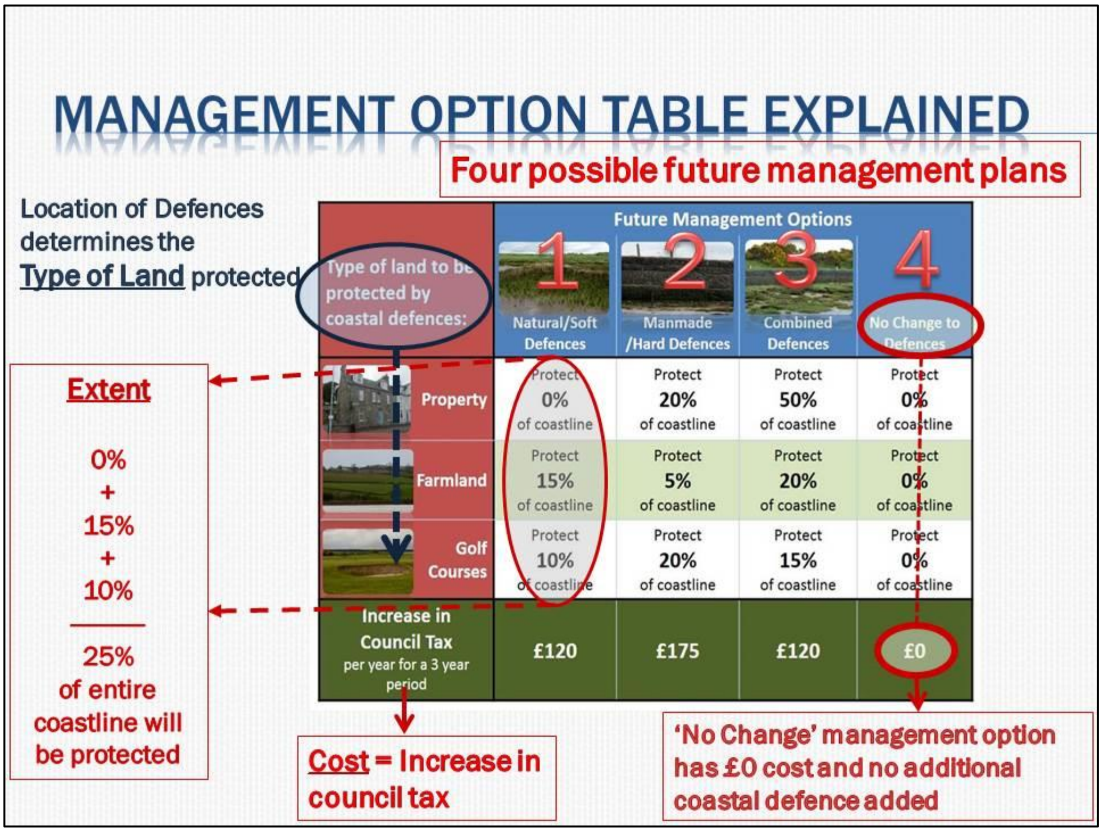


Figure 5.4: Screen shot taken from information video for choice experiment explaining a choice card and how to interpret it.

5.4.3 Focus Groups

Prior to collecting data, three focus group meetings of between 7 and 10 local residents were carried out, in order to assess understanding of the information video, the clarity of the choice cards and realism of the scenarios proposed by the experiment.

The information video was played followed by an open discussion to establish how much was understood and whether the length was appropriate. A selection of choice card designs was then presented (Figure 5.5 a - c) and participants were asked to discuss and vote on their preferred design. Choice card d (Figure 5.5) was the final design used which combined features of the designs presented in the focus groups and open suggestions.

A discussion relating to the cost attribute and appropriate levels was discussed. The realism of using council tax as a cost vehicle and the believability that this would occur in reality were both felt to be relevant. The cost levels presented, which were based on the estimated cost of installing defences in the Eden estuary, were felt to be acceptable given the proposed provision of coastal flood defences. The participants were not informed of the process by which these costs were conceived.

The final task for the participants was to complete a short survey asking their opinions on the appropriate length for the survey if they were to complete it online and if they were stopped on the street (intercept survey). In addition, their general opinions on the survey design, reality and usefulness were asked.

Figure 5.5: (a – c) Sample choice card designs presented at the focus groups. d) Final choice card design used for survey.

The feedback received through the focus group and survey was incorporated into the survey design with minimal changes being made to the information video and choice card design.

5.4.4 Choice Set Generation

A labelled design was used with each choice card within the choice set having all alternatives present and there being six levels of each alternative as appropriate, forming a balanced orthogonal design. A total of 24 choice cards divided into three blocks of eight were produced using the statistical software NGENE. The D_{error} for the design of the pilot survey choice set was of 0.218. A D-efficient design (low D_{error}) aims to minimise the covariances of parameter estimates, reducing the standard error and therefore enabling a lower number of observations (respondents) to provide a statistically significant model. It also ensures that choice cards with identical alternatives or dominant alternatives are generated (Hensher, Rose and Greene, 2015). NGENE uses simple randomisation and swapping heuristics on the attribute level to achieve this.

5.4.5 Survey Testing

Testing the design of both the choice sets and the survey prior to the main data collection is required to minimise the likelihood of any misunderstandings ensuring that estimates made are appropriate.

5.4.5.1 Pilot Survey

A pilot survey was conducted over a six-week period between October and November of 2013. In addition to the choice experiment cards and questionnaire this was an opportunity for respondents to comment on the survey structure, length and clarity. An invite to complete the survey online was sent to mailing lists for a local adult college, a rugby club and kayaking group. A total of 40 responses were recorded each completing 8 choice cards.

The data was analysed using NLOGIT and a conditional logit model (CLM) was used (Table 5.3). A significant price coefficient was estimated. Significant positive coefficients were estimated for soft defences, combined defences and property. Coefficients for hard defences, farmland and golf fairways were not significant.

Table 5.3: Results from conditional logit model for pilot choice experiment data (n (observations) = 288, n (individuals) = 40, pseudo R^2 = 0.11). Grey text indicates non-significant results.

Alternative	Coefficient, β	Standard Error	Probability	WTP (per household)
Soft Defences	1.337	0.398	0.0008	£835.63
Hard Defences	-0.004	0.411	0.9919	NA
Combined Defences	1.47	0.389	0.0002	£918.56
Property	0.029	0.004	>0.000	17.82
Farmland	0.004	0.009	0.612	NA
Golf fairways	-0.008	0.009	0.339	NA
Price	-0.002	0.001	0.002	NA

The estimated WTP was higher than the maximum price included in the choice options (£600) consequently the levels of the price attribute were changed for the main survey with a maximum increase in council tax of £900 per household over a three-year period (Table 5.4).

Of the 40 respondents that completed all the choice cards, 28 completed the additional questions relating to the survey design. In general, the feedback was positive with very few negative responses (Table 5.4).

Table 5.4: Summary of the responses to questions relating to the survey design (n = 28). Responses were based on a Likert scale. Mean scores range between -2 and +2 with -2 representing a negative response and +2 a positive.

Question	Score
Was the video an appropriate length?	0.75
Was the information in the video clear and understandable?	1.64
Did the video explain the purpose of the video clearly?	1.71
Did you clearly understand what was meant by coastal flood defence and the management options available?	1.93
Did you clearly understand what was meant by the types of property that could be defended?	1.82
Did you clearly understand what was meant by the extent of coastline protected?	1.75
Were the management scenario questions (choice cards) easy to understand and complete?	0.79

5.4.5.2 Intercept Surveys

When initially designing the survey, data collection methods included the use of intercept surveys where people were stopped in a public place and asked to complete the survey. This was trialled in several public locations within the target area using tablets however the uptake was low. Those who did agree to complete the survey commented that it took too long and several left having only completed the choice cards. Due to the cost and poor response rates it was decided that it was not an appropriate method for data collection for this survey.

5.5 Main Survey

5.5.1 Choice Set Generation

The covariates estimated in the CLM for the pilot study were used as the priors when modelling the choice set for the main survey as this has been found to produce a more D-efficient design (Hensher, Rose and Greene, 2015). The D_{error} for the design was 0.120.

5.5.2 Data Collection

Data collection for the main survey began in March 2014 via an online survey. A website hosted by the University of St Andrews was built and hosted the survey. A full copy of the survey can be found in Appendix B. The survey was advertised through social media, by placing posters and flyers in shops, schools, community centres and transport hubs located within the target area and sending invites out via mailing lists. In addition to this approximately 15 short presentations were given to local community and council groups introducing the survey and asking those present to promote the survey. A mail shot was also sent to 250 households within the target area inviting them to complete the survey online.

In November 2015 due to the number of responses declining and the need for additional responses a consultancy was used to send an invitation to complete the survey to 10,000 e-mail addresses within the target area via an e-mail panel. A prize draw for shopping vouchers was offered as an incentive. The survey was closed in February 2016.

5.5.3 AnalysisData Collection

Analysis of the CE data using random utility models was completed used Stata 13 (StataCorp, 2013). Conditional logit (CLM) and mixed logit models (MLM) were used to analyse the CE data. Log likelihood was used to compare between the models with the smallest value corresponding to the model with the least deviance. The command ‘clogit’ was used for the CLM. The ‘mixlogit’ package was used for the MLM. WTP was calculated using the ‘wtp’ command and the Delta method. Unless otherwise stated all attributes were assumed to have a normal distribution. The MLM model was used to incorporate preference heterogeneity. More information about the differences between the models can be found in the methods chapter section 2.2.

Analysis of other survey questionnaire data was completed using Microsoft Excel.

5.6 Results

In total 185 completed responses were received from residents within the target area representing 0.35% of the number of households in the target area. Of the responses, 66 were from the social media and presentation campaign, 102 were from the e-mail panel (1.02% response rate) and 17 from the postal survey (6.8% response rate). An additional 62 responses were only partially completed with respondents leaving before completing the choice card section. These were excluded from the data set giving a completion rate of 74.8% for those who started the survey. The amount of time spent completing each question was monitored and used to determine whether respondents remained on the background information video page for the full length of the video. All 185 responses used in the analysis remained on the background information page of the survey for at least the minimum length of time it would take to watch the full video.

Respondents were asked whether they believed that the results from the survey would be shared with policy makers. Only 6% did not believe this, with an overwhelming majority of 87% believing that it would be shared with policy makers (Figure 5.5).

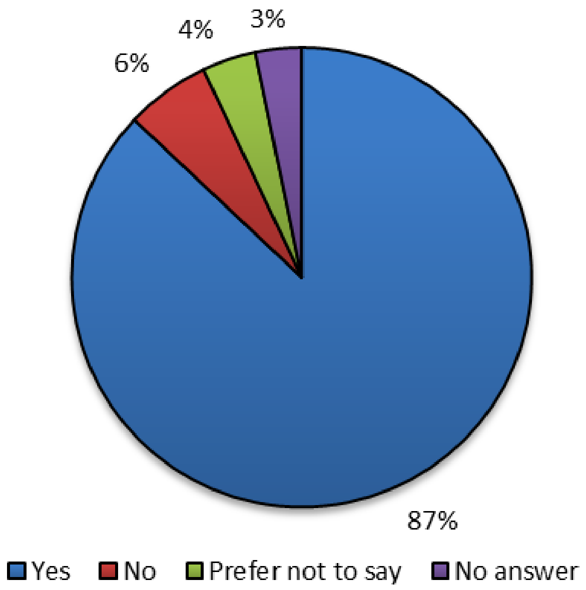


Figure 5.5: Respondents response to the question ‘Do you believe that the results of this survey will be shared with policy makers?’ The survey refers to the choice experiment and questionnaire (n = 185).

5.6.1 Respondents Characteritics

A summary of respondents self-reported socio-demographic characteristics are presented (Table 5.5). Where available these data were compared to Scottish Neighbourhood Statistics for Fife (The Scottish Government, 2013).

Table 5.5: Summary of self-reported socio-demographic characteristics of the participants (n=185).

	Percentage of sample
Gender	
Male	59.5
Female	38.4
Prefer not to answer	2.2
Age	
under 18	0.5
18 - 24	8.6
25 - 34	21.6
35 - 44	17.3
45 - 54	21.1
55 - 64	14.1
65+	14.6
Prefer not to say	2.2

Employment Status	
Full time (35 + hr)	52.4
Part Time (<35 hr)	11.9
Stay at home parent	3.8
Student	8.6
Retired	16.8
Unemployed	0.0
Self employed	2.7
Prefer not to say	3.8
Annual Household Income	
Under £10,000	1.6
£10,000 - £14,999	3.2
£15,000 - £19,999	5.9
£20,000 - £24,999	10.3
£25,000 - £29,999	12.4
£30,000 - £39,999	16.8
£40,000 - £49,999	14.6
£50,000 - £69,999	11.4
Over £70,000	2.7
Prefer not to say	21.1
Location of Property	
Target area (North East Fife)	76.8
Fife	17.8
Angus	3.2
Prefer not to say	2.2
Property Status	
Owner	63.2
Rent	27.6
Live rent free	2.7
Other	4.3
No answer	2.2
Property at risk of flooding	
Yes	23.8
No	64.9
Don't Know	9.2
No answer	2.2
Member of conservation group	
Yes	47.6
No	49.2
Prefer not to say	1.1
No answer	2.2

5.6.1.1 Age and Sex

More responses were completed by males than females with males being overrepresented compared to the region statistics (47% male) (The Scottish Government, 2013). The most common age groups were 25 – 35 years (21.6%) and 45 – 54 years (21.1%). The younger age groups (under 25 years) were poorly represented with only 9.1% of the respondents from these groups compared to 22% in the region (The Scottish Government, 2013). The age groups over 35 years were well represented. Except for the 18 - 21 years and the 25 – 34 years age categories there were more male respondents than female (Figure 5.6).

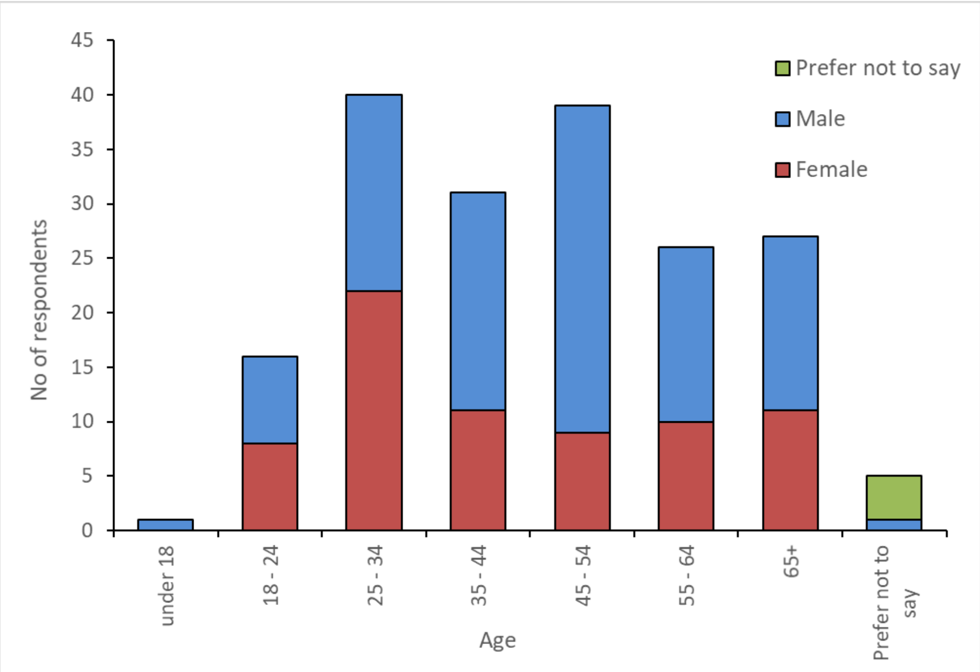


Figure 5.6: Survey respondents by sex and age (n = 185).

5.6.1.2 Employment and Household Income

Over half of the respondents were employed full time (52.4%), a further 11.9% were employed part time and 2.7% were self-employed (Table 5.5). None of the respondents were unemployed. Full and part time students made up 8.6% of the respondents and 3.8% were stay at home parents. 16.8% of the respondents were retired.

Respondents were asked what their gross annual household income before tax was. The responses were grouped into the brackets in Table 5. The modal household annual income of £30000 - £39999 (16.8%) was higher than the median income for the region (£26,000; SNS, 2006). The three lowest household income groups (under £20000) and the highest income group each consisted of under 6% of the respondents. Over a fifth of the respondents (21.1%) chose not to provide their household income (Table 5.5).

5.6.1.3 Location of Participants

Over three quarters of the respondents were from the target area of north east Fife (76.8%; Table 5.5). Of the remaining responses 17.8 % were from Fife, 3.2% from Angus. The respondents from Angus were included in the analysis as they were from Dundee (2.7%) or Broughty Ferry (0.5%) (Figure 5.7), both of which are a short distance from the Eden estuary. The majority of respondents were from St Andrews (21.6%), followed by Cupar (15.7%), Guardbridge (11.4%), Leuchars (9.2%), Tayport (6.5%), Newport on Tay (3.8%) and Balmullo (3.2%) (Figure 7). The remaining locations each represented less than 2% of the responses received.

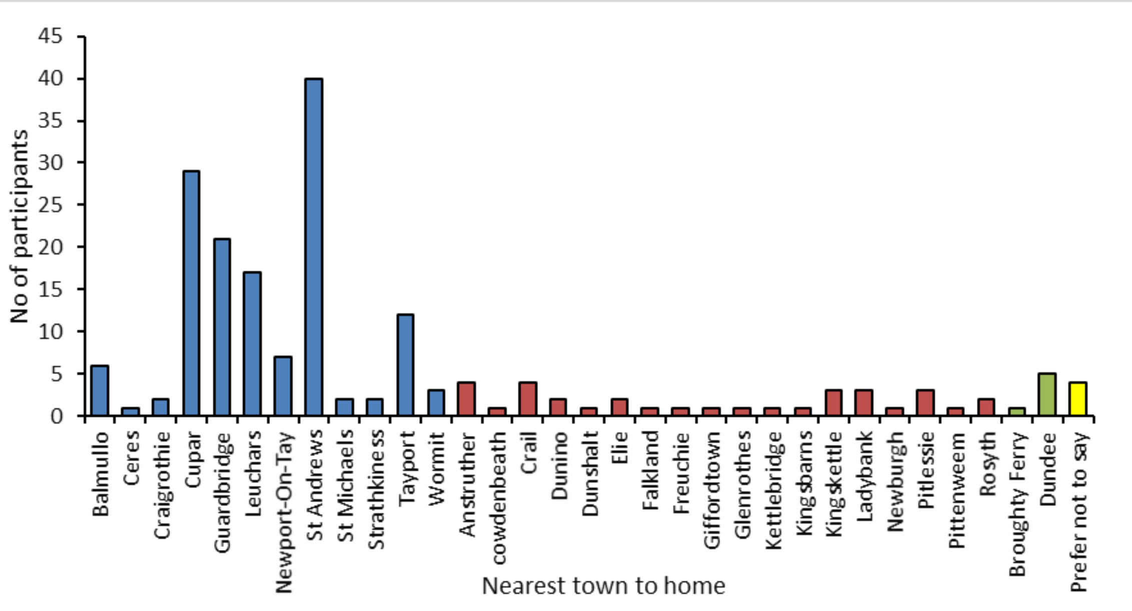


Figure 5.7: Location of respondents' homes based on their nearest town (n = 185). Blue bars represent the responses received in the target area of north east Fife (see Figure 5.1), red bars represent towns in Fife but outside of target area, green represents towns in Angus, and yellow all other responses.

5.6.1.4 Property Status and Perception of Flood Risk

Most of the respondents owned their property (63.3%) which was representative of the population in Fife (64% home owners, SNS, 2006). Less than half this number rented their property (27.6%) (Table 5.5). Almost two thirds of the respondents did not perceive their property to be at risk from coastal flooding, 9.2% did not know and 23.8% believed their property to be at risk from coastal flooding (Table 5.5).

5.6.2 Use of the Eden Estuary

Of the 185 responses received 6% had never visited Tentsmuir Park, over half (56%) had visited it at least monthly and a third (34 %) had visited it less often than monthly (Figure 5.8). The Eden visitor centre and the bird hides around the Eden and Tentsmuir had never been visited by many of the respondents (49% and 44% respectively). Only 15% of the respondents visited the Eden Centre and 13% the bird hides monthly or more frequently.

Respondents were asked whether they participated in golf, birdwatching or wildfowling. Over a third of the respondents stated that they went birdwatching (36%), almost a quarter (24%) stated that they played golf and tenth stated that they went wildfowling (Figure 5.9)

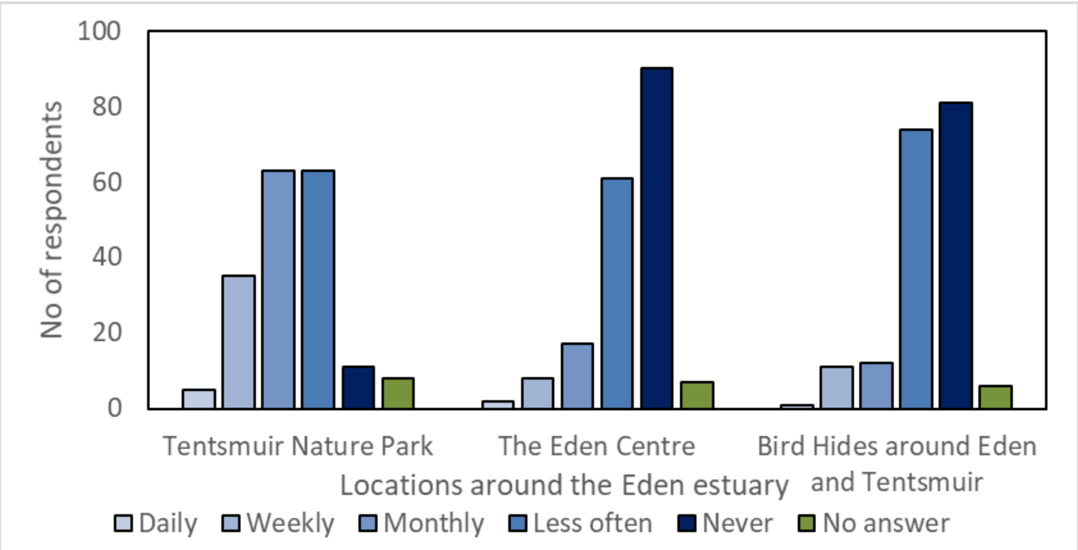


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Figure 5.8: The frequency with which respondents visited areas or attraction around the Eden estuary (n = 185).

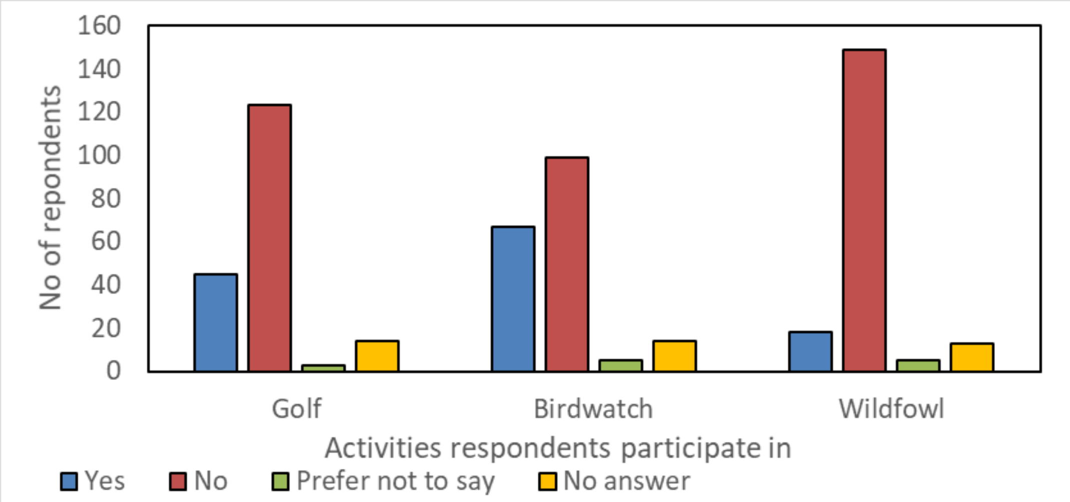

Figure 5.9: Respondents participation in activities common around the Eden Estuary (n = 185).

5.6.3 Choice Experiment

Of the 185 completed surveys, 70 respondents completed choice block 1, 64 completed block 2 and the remaining 51 completed block 3.

Only 10 respondents answered ‘status quo’ (no change to coastal defences with zero cost associated) to all 8 choice cards within their choice set (Figure 5.10). Two of these completed block 1, five block 2 and three block 3. Most respondents did not opt for status quo when answering any of their choice cards (112, 60.5 %).

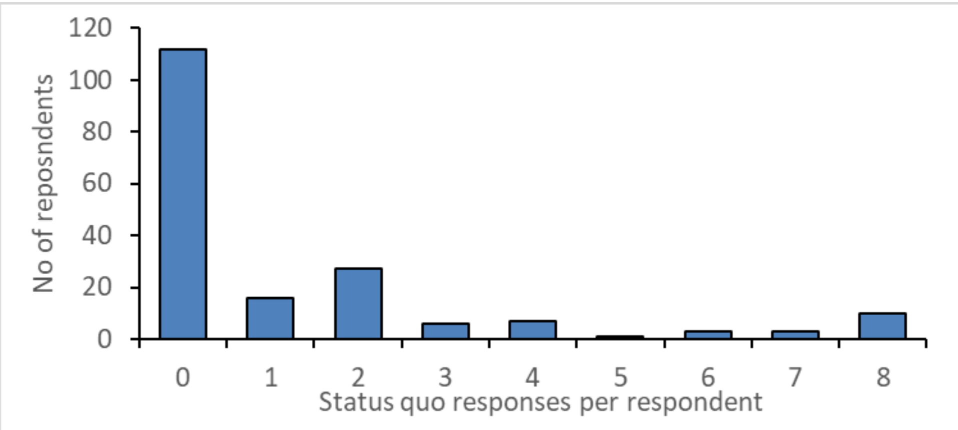

Figure 5.10: The number of status quo responses recorded by each respondent when completing the choice set which consisted of eight cards (n = 185).

5.6.3.1 Conditional Logit Model

A CLM was fitted using all environmental attributes for the 185 responses received. Alternative specific constants (ASCs) were estimated for soft, hard and combined defences with *status quo* being the baseline to which these are compared. The model had a log likelihood of -1824.8 and a pseudo r^2 of 0.11 (n (observations) = 5920; n (individuals) = 185). The estimated beta (covariate) values and probabilities are in Table 5.6.

The beta value for price was negative and significant. The ASC parameters for the types of flood defence were all significant (at the 0.005 level or higher). Soft defences and combined defences both had positive values indicating that respondents would prefer these management scenarios over the *status quo*, ‘do nothing’ option. The covariate for combined defences was marginally higher than for soft defences implying that the most preferred scenario would be combined defences. The hard defence scenario had a negative covariate value indicating that the respondents do not prefer this over the *status quo* option and would not be willing to pay for this change.

With respect to the type of land to be protected beta values for property and farmland were both positive and significant at the 0.0001 level indicating that the respondents valued protecting these types of land. Property had a higher beta value than farmland suggesting a greater value is placed on defending property from coastal flooding than farmland. The beta value for golf fairways was negative and not significant indicating that the respondents on average did not gain any benefit from protecting golf fairways.

Willingness to pay (WTP) estimates (Table 5.7, Figure 5.11) replicate the same pattern as the beta value with people WTP more than 2.5 times as much to protect property compared to farm land. A negative WTP was estimated for golf fairways, however this was not significant. Combined defences had the highest WTP, followed by soft defences. A large negative WTP was estimated for hard defences.

Table 5.6: Conditional Logit Model estimating people's preference for different types of flood defence (soft, hard and combined) and for protecting different types of land (property, golf fairways and farm land). Log likelihood = -1824.8, pseudo $r^2 = 0.11$, n (observations) = 5920; n (individuals) = 185. Grey text indicates a statistically insignificant result.

Attribute or Alternative	Coefficient, β	Standard Error	z	P > z	95% confidence interval	
					lower	upper
Price	-0.001	0.000	-4.36	0.000	-0.001	0.000
Property	0.029	0.004	7.10	0.000	0.021	0.037
Golf Fairways	-0.004	0.004	-1.05	0.294	-0.012	0.004
Farm Land	0.012	0.002	4.91	0.000	0.007	0.016
Soft Defences	0.409	0.136	3.01	0.003	0.142	0.675
Hard Defences	-0.916	0.166	-5.51	0.000	-1.241	-0.590
Combined Defences	0.465	0.141	3.29	0.001	0.188	0.742

Table 5.7: Willingness to Pay estimates for type of coastal defence and type of land protected in the Eden estuary, Fife. Values represent the total increase in council tax per household over a three-year period. Estimated using choice experiment data and conditional logit model. Grey text indicates statistically insignificant results.

Willingness to Pay (£/household over a three year period)	Type of Land Protected			Type of Coastal Defence		
	Property	Golf Fairways	Farm Land	Soft	Hard	Combined
Mean	56.21	-8.36	22.36	784.48	-1757.38	892.15
Lower estimate	24.87	-24.41	8.98	277.30	-2949.89	391.52
Upper Estimate	87.55	7.68	35.74	1291.67	-564.86	1392.78

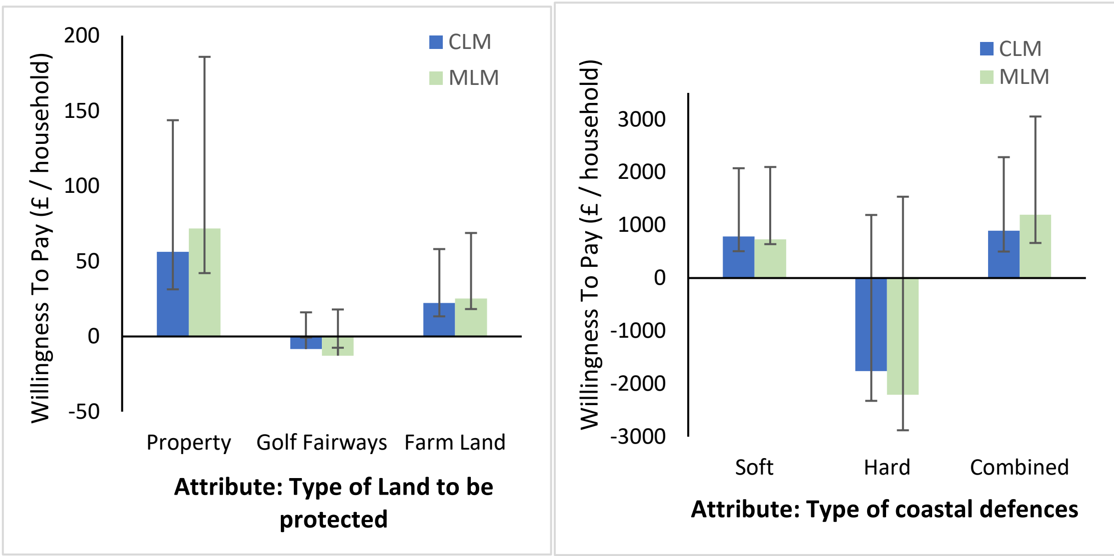

Figure 5.12: Willingness to pay estimates for coastal defences in the Eden estuary, Fife. Blue bars represent estimates using a conditional logit model (CML), green bars represent estimates using a mixed logit model with fixed price (MLM).

5.6.3.2 Mixed Logit Model with Fixed Price

A mixed logit model was fitted using all attributes and levels for the 185 responses received. Alternative specific constants (ASCs) were estimated for soft, hard and combined defences with *status quo* being the baseline to which these were compared. All choice attributes were included as random parameters to account for unobserved variation in the respondents' preferences and specified as having a normal distribution. The model had a log likelihood of -1586.8 (n (observations) = 5920; n (individuals) = 185) which was lower than that of the CLM and therefore a better fit. The estimated beta values and their standard deviation are presented in Table 5.8.

The beta parameter for price was negative and significant. The ASC parameters for type of flood defence were all significant. Like the CLM output the parameters for soft and combined defences were positive indicating that either of these scenarios is preferred over the *status quo* option. Again, combined defences were found to have a higher parameter than soft defences suggesting that this would be the preferred scenario by the respondents. The parameter for hard defences was again found to be significant and negative implying that the respondents would prefer the *status quo* option over the hard defence scenario. The standard deviations for all types of defences were found to be significant suggesting that there is a high degree of unobserved heterogeneity across individuals choices for all types of defence available.

Like the CLM, mean beta values for protecting property and farmland were found to be significant and positive suggesting that the respondents valued protecting these types of land. Again, golf fairways had a non-significant beta value implying that the respondents did not gain any value from protecting this type of land. The standard deviation for these attributes, including golf fairways, was found to be significant suggesting that there was a significant degree of heterogeneity in peoples' preferences. The density plots for mean beta values for all attributes are presented (Figure 5.13) indicating the high degree of variability.

With respect to the type of coastal defence, combined defences received the highest WTP with a value 1.6 times that of soft defences (Table 5.9, Figure 5.12). Hard defences received a high negative WTP. WTP estimates for hard and combined defences were more extreme using the MLM than the CLM. The WTP for soft defences was marginally less using the MLM compared to the CLM (Figure 5.12).

The estimated WTP for property was 2.8 times higher than that for farm land and a negative WTP was estimated for golf fairways however this was not significant. All values relating to the type of land being protected were more extreme when estimating WTP using the MLM than the CLM (Figure 5.12).

Table 5.8: Mixed Logit Model estimating people's preference for different types of flood defence (soft, hard and combined) and for protecting different types of land (property, golf fairways and farm land). Model was estimated with all attributes random except for price which was fixed. Log likelihood = -1586.8, n (observations) = 5920; n (individuals) = 185. Grey text indicates a statistically insignificant result.

Attribute or Alternative	**Coefficient, β**	**Standard Error**	**z**	**P > |z|**	**95% confidence interval**	
					lower	**upper**
Mean values						
Price	-0.001	0.000	-3.98	0.000	-0.001	0.000
Property	0.043	0.006	7.10	0.000	0.031	0.055
Golf Fairways	-0.008	0.005	-1.46	0.143	-0.018	0.003
Farm Land	0.015	0.004	3.54	0.000	0.007	0.024
Soft Defences	0.440	0.198	2.22	0.026	0.052	0.828
Hard Defences	-1.332	0.251	-5.32	0.000	-1.824	-0.841
Combined Defences	0.721	0.195	3.70	0.000	0.340	1.103
Standard Deviation						
Property	0.045	0.006	7.70	0.000	0.057	0.034
Golf Fairways	0.020	0.008	2.36	0.018	0.036	0.003
Farm Land	0.044	0.004	10.08	0.000	0.035	0.053
Soft Defences	1.430	0.148	9.65	0.000	1.721	1.140
Hard Defences	1.377	0.222	6.19	0.000	0.941	1.813
Combined Defences	1.239	0.163	7.58	0.000	0.918	1.559

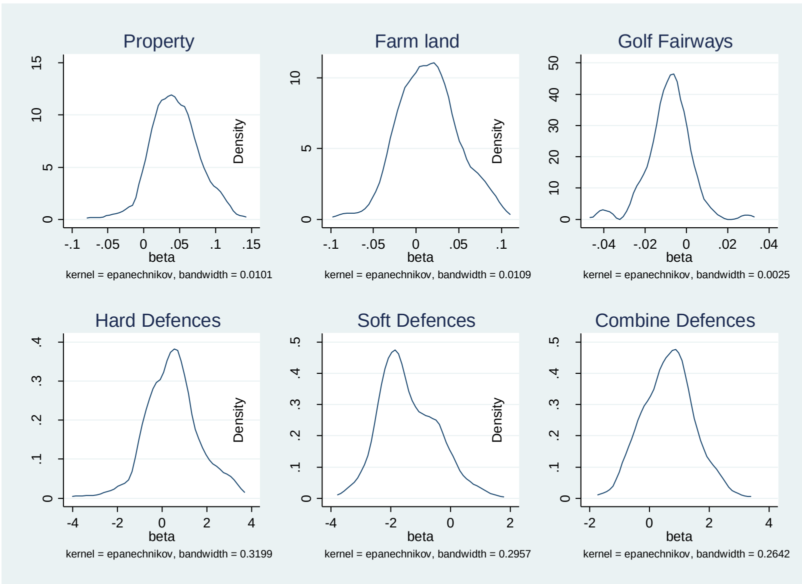

Figure 5.13: Plots of the beta distribution for all random attributes in the mixed logit model with fixed price showing the degree of heterogeneity in the respondents' preferences. This was found to be significant for all attributes.

Table 5.9: Willingness to Pay estimates for type of coastal defence and type of land protected in the Eden estuary, Fife. Estimated using choice experiment data and mixed logit model with fixed price. Grey text indicates statistically insignificant results.

Willingness to Pay (£/household over a three year period)	**Type of Land Protected**			**Type of Coastal Defence**		
	Property	**Golf Fairways**	**Farm Land**	**Soft**	**Hard**	**Combined**
Mean	71.89	-12.75	25.28	729.21	-2207.87	1195.53
Lower estimate	29.76	-30.72	7.05	88.69	-3745.27	532.66
Upper Estimate	114.01	5.22	43.52	1369.73	-670.47	1858.41

5.6.3.3 Mixed Logit Model with Random Price

A mixed logit model was fitted using all attributes and levels for the 185 responses received. All attributes were random to account for any unobserved heterogeneity in the respondents' preferences. Alternative specific constants (ASCs) were estimated for soft, hard and combined defences with *status quo* being the comparative baseline. Price was also random and specified as having a log normal distribution to ensure the covariate estimate was negative for all individuals and prevent counter-intuitive values. The model had a log likelihood of -1534.9 (n (observations) = 5920; n (individuals) = 185) which was lower than that of the CLM and the MLM with fixed price. The estimated beta values and their standard deviation are provided (Table 5.10).

The beta value for price was negative and significant. The standard deviation for price beta values was also found to be significant revealing unobserved heterogeneity across individuals choices.

The ASC parameter estimates for the types of flood defences were all significant. Once again, as with the CLM and MLM with fixed price, soft defences and combined defences both had positive outcomes indicating that these scenarios are preferred over the *status quo* scenario with combined defences having a higher beta value. Once again, hard defences had a negative beta value indicating that the respondents would prefer the *status quo* option over this scenario.

Mean beta values for the type of land protected followed the same pattern as for the other two models with property and farmland having significant positive values and golf fairways having a non-significant value. Once again this indicated that respondents value protecting property and farmland but did not think they gained any value by protecting golf fairways.

Unlike with the MLM with the fixed price model, standard deviation for combined defences parameter was not significant indicating that there was no unobserved variability between the respondents' choices with respect to this type of defence. All other metrics standard deviations were found to be significant indicating heterogeneity across individuals' choices for all attributes (Figure 5.14).

Table 5.10: Mixed Logit Model estimating people's preference for different types of flood defence (soft, hard and combined) and for protecting different types of land (property, golf fairways and farm land). Model was estimated with all attributes including price as random. Log likelihood = -1534.9, n (observations) = 5920; n (individuals) = 185. Grey text indicates a statistically insignificant result.

Attribute or Alternative	Coefficient, β	Standard Error	z	P > |z|	95% confidence interval	
					lower	upper
Mean values						
Price (ln)	-8.699	0.495	-17.56	0.000	-9.670	-7.728
Property	0.040	0.006	7.25	0.000	0.029	0.051
Golf Fairways	-0.007	0.005	-1.35	0.178	-0.017	0.003
Farm Land	0.015	0.004	3.76	0.000	0.007	0.023
Soft Defences	1.194	0.196	6.09	0.000	0.810	1.578
Hard Defences	-0.795	0.259	-3.07	0.002	-1.301	-0.288
Combined Defences	1.313	0.174	7.55	0.000	0.972	1.655
Standard Deviation						
Price (ln)	4.723	0.556	8.50	0.000	5.813	3.633
Property	0.034	0.006	5.26	0.000	0.021	0.047
Golf Fairways	0.015	0.007	2.12	0.034	0.001	0.028
Farm Land	0.038	0.004	10.02	0.000	0.030	0.045
Soft Defences	1.393	0.133	10.45	0.000	1.132	1.655
Hard Defences	1.492	0.240	6.21	0.000	1.020	1.963
Combined Defences	0.156	0.212	0.74	0.462	0.259	0.571

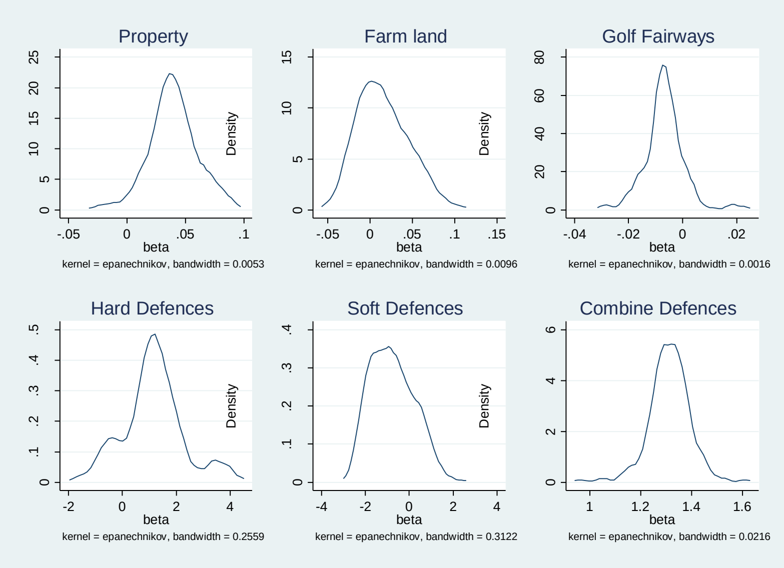

Figure 5.14: Plots of the beta distribution for all random attributes in the mixed logit model with fixed price showing the degree of heterogeneity in the respondents' preferences. This was found to be significant for all attributes.

5.6.3.4 Mixed Logit Model with Random Price and Perception of Flood Risk Interaction

Preference heterogeneity across respondents identified in the previous MLM models was investigated through introducing an interaction into the model. The interaction introduced examined whether the respondents who perceived their property to be at flood risk (Risk) placed different levels of utility on the different types of coastal defence. As with the MLM with random price, all attributes were treated as random and as having a normal distribution except for price which was estimated using a lognormal distribution. Risk was interacted with all three of the ASC (types of flood defences). The log likelihood value, -1517.1 was an improvement on the other models suggesting a better fit to the data (Table 5.10).

The beta value for price was negative and significant. The standard deviation for price beta values was also found to be significant revealing unexplained heterogeneity across individuals choices.

The ASC parameter for soft and hard defence scenarios were not significant. The ASC parameter for combined defences was significant and positive indicating that this is the only scenario that was preferred over the *status quo* option when the respondents' perception of risk of flooding was included in the model. The beta value for the interaction between soft defences and risk was significant and positive, unlike the interactions with hard and combined defences. The positive value indicates that respondents who believed their property to be at risk from flooding were more likely to select a soft defence scenario than those who did not perceive their property to be at risk from flooding. The standard deviation of the parameters was significant for all interaction terms. It was also significant for the parameter for soft defences and hard defences meaning that there are still variances between the respondents choices that are unexplained.

The beta values relating to the type of land protected were significant and positive for property and farmland. The standard deviation for these parameters was also significant indicating that there is unobserved heterogeneity between the individuals' choices. The beta estimate and standard deviations for golf fairways were both insignificant suggesting that the respondents did not gain any value in protecting golf fairways. These results were similar to other models employed so far.

Table 5.11: Mixed Logit Model estimating people's preference for different types of flood defence (soft, hard and combined) and for protecting different types of land (property, golf fairways and farm land). Interaction between respondents who perceived their property to be at risk from flooding (Risk) and other attributes. Model was estimated with all attributes including price as random. Log likelihood = -1517.1, n (observations) = 5920; n (individuals) = 185. Grey text indicates a statistically insignificant result.

Choice	Coefficient	Standard Error	z	P > |z|	95% confidence interval	
					lower	upper
Mean values						
Price	-8.709	0.504	-17.29	0.000	-9.697	-7.722
Property	0.039	0.005	7.25	0.000	0.028	0.050
Golf Fairways	-0.007	0.005	-1.41	0.159	-0.017	0.003
Farm Land	0.016	0.004	3.73	0.000	0.007	0.024
Soft Defences	-0.252	0.555	-0.45	0.649	-1.339	0.835
Hard Defences	-0.555	0.555	-1.00	0.317	-1.642	0.532
Combined Defences	0.866	0.428	2.02	0.043	0.027	1.705
Soft*Risk	0.794	0.288	2.76	0.006	0.229	1.358
Hard*Rik	0.004	0.294	0.01	0.990	-0.572	0.579
Comb*Risk	0.279	0.229	1.22	0.222	-0.169	0.727
Standard Deviation						
Price	-3.201	0.368	-8.70	0.000	-3.922	-2.479
Property	-0.029	0.006	-5.04	0.000	-0.040	-0.017
Golf Fairways	0.013	0.010	1.34	0.181	-0.006	0.032
Farm Land	0.041	0.004	9.12	0.000	0.032	0.049
Soft Defences	-1.084	0.164	-6.61	0.000	-1.405	-0.762
Hard Defences	0.984	0.290	3.39	0.001	0.416	1.552
Combined Defences	-0.281	0.393	-0.71	0.475	-1.051	0.490
Soft*Risk	0.460	0.099	4.65	0.000	0.266	0.653
Hard*Rik	0.391	0.145	2.70	0.007	0.107	0.676
Comb*Risk	0.175	0.075	2.33	0.020	0.028	0.323

5.6.4 Factors Influencing Respondents Decisions in Choice Set

The initial question that gauged the respondent's preference for the type of defence indicated that there was preference for soft defences with a mean value of -40.4 ±47.2 where -100 represented soft defences and +100 represented hard defences. Participants responses ranges between -100 and +98 and the high standard deviation shows that there was a lot of variability in the responses.

All the factors presented were found to be important in participants decisions when completing the choice set (Table 5.12). Time until the defence is effective was found to be the least important.

Participants were asked to place four factors that influenced their decisions relating to the choice sets in order of importance (Appendix B, Figure 5.9). The extent of the defence was the least important with 52 % of the respondent ranking it in last place (Figure 5.15). The type of coastal defence was the most influential with 34 % ranking it as the most important and a further 30 % ranking it as the second most important. The initial cost of the defence was the second most important with 33 % ranking it first and 19 % ranking it second, however a quarter of the participants also ranked this as the least important. The type of land being protected was placed as the most important 30 % of the time and the second most important 37 % of the time, however it was placed as the least important by the smallest proportion of the participants (6 %).

Table 5.12: Factors influencing participants decisions regarding coastal flood defences in the Eden estuary (n = 185). Measured using a Likert scale where 2 represented very important, 0 neutral and -2 very unimportant.

	Mean Likert Scale
Time until defence is effective	0.6
What it looks like / aesthetics	1.1
Cost of on-going maintenance	0.9
Initial cost of defence to participant	1.0
Provision of habitat for wildlife	1.2

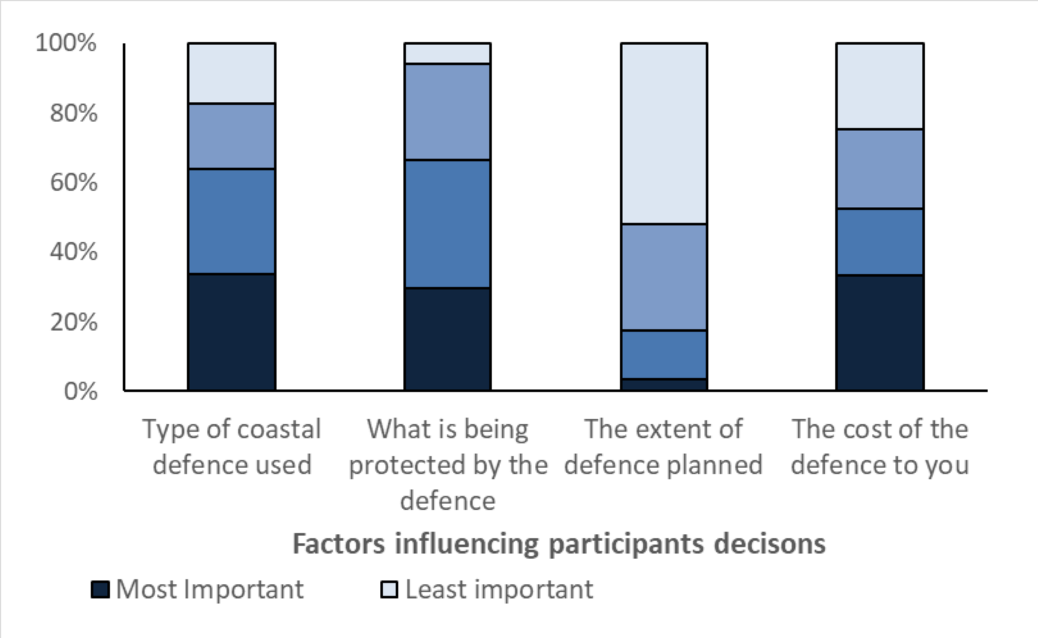

Figure 5.15: The importance of factors influencing participants decisions when completing the choice sets related to coastal flood management in the Eden estuary. Participants were asked to order the four factors in relation to how influential they were when selecting the management option (n = 166). Dark blue indicates the most important, light blue indicates the least important.

5.6.5 Open Comments

In total 42 open responses were provided (Table 13).

Table 13: Comments provided by survey respondents. The grey filled cells indicate the respondents who opted for the '*status quo*' scenario in all scenarios

ID	COMMENT
23	I am most concerned with protecting personnel property, and flooding near the airbase/train station which could drastically impact personnel quality of life.
28	As an environmental scientist I value the local ecology and wildlife more than I value other people's property.
42	flooding of surrounding land unimportant e.g. airfield, golf course.
55	As a active wildfowler on the Eden estuary I feel it is vital that natural/soft defences are used to improve habitat for the wildlife that use the estuary. The long-term benefits are easy to see i.e. natural/soft defence are cheaper and better for the estuary and they will fit in with the environment.
82	I would be in favour of NOT protecting golf courses at all, but I didn't see an option for that.
84	I don't recall any major flooding in these areas in my lifetime except Kinnesburn which flooded maybe twice in my life, I am 54
93	my property was flooded in December 2012 due to the river Eden bursting it's banks and flooding over farmland then on to houses
99	There is an existing concrete and rip/rap wall at Guardbridge Paper Mill which should not be forgotten about. This protects the village of Guardbridge as well as the mill site. No mention of this is made in the survey video.
101	Nature will win in the long road anyway.
102	Extent of defence is important, but what really matters is 'whether or not MY house is protected'. It could only be 10% of coastline, but if my property is protected then I'm willing to pay.
117	I only opted for one no change scenario. this is because it was weighted too heavily towards protecting the golf courses. I feel that the courses should invest in their own protection, with minimal subsidies from the council etc in order that properties and farm land can be suitably defended.
122	Loss of land to rising sea level is inevitable but managed retreat was not presented as an option.

123	Whilst property was one of the major categories- I was left unsure if this also included 'infrastructure'- the most immediate threat to my well-being looking at the SEPA floodmaps seems to be the potential flooding of the A91- although this is behind 'farmland', it would have an impact on infrastructure (hence an uncertainty about which category to tick for my responses). to be clear I have assumed your category of 'property' also includes 'infrastructure'. Protecting golf courses- I assume this refers to the world famous Links course, and the fact that it was this course rather than 'any' golf course probably affected my views on whether it is cost-effective to defend. In general I feel that we can't avoid the likelihood that sea levels will rise so 'do nothing' is not really an option- hence a willingness to spend moderate amounts of money over do nothing scenarios, yet I feel we also have to learn to live with change and work with nature- therefore I feel that human adaptation with some (limited?) defences offers the best way forward. I am not a fan of the way that big engineered concrete defence structures would marr the landscape and interfere with natural sediment cycles. Yet with your 'combined option', I was not convinced from the information presented that this option could be effective- would not the habitat just be squeezed against the wall with rising sea levels?
131	I do not think councils & governments will be able to protect low lying areas and coastlines from sea level rises. We somehow must allow nature to do what it does, most of coastline is dynamic. There has to be a change in planning and prevent future building in flood plains and low coastlines.
152	The golf courses are of prime importance to St Andrews --- the rest can be replaced if necessary but the Old Course cannot.
155	Let nature take its course. We should not be building on areas where flooding is likely. The current problems are largely due to ignorance of nature
157	Those who use golf courses should pay for the flood defences of the facility, not the Council.
159	Poorly presented set of questions - virtually no difference between question screens 1-8 made it appear as if the same question was being repeatedly asked. And did I see a picture from the Dura Den flood in that video? Looked like it - if so, that's not coastal flooding but manmade flooding caused by council incompetence/inaction. If not, please disregard this comment.
173	Has to be Comprehensive and through
174	From an ecological and aesthetic point of view, I would like to see the optimal use of natural defences.
178	Manmade hard protection should be limited to property protection only and when it is the only option.
187	I opted for 'no change' on one question because it seemed very expensive to protect only 10% of each land type
189	The protection for the golf courses should also be funded by St Andrews Links and the Royal & Ancient. With the amount of money in golf and the commercial importance to them of protecting this land they should more than share the burden
191	need balance between cost and amount/kind of land saved

192	I'm afraid the scenarios presented were very confusing and the questions were not clear to me, so please ignore the answers I have submitted!!
193	World wide, schemes that work in harmony with nature are, long-term, the most effective and using soft defences to greatly extend natural habitat will offset the dreadful habitat lost upstream in the Eden where factory and industrial farming by Kettle produce and its suppliers has decimated woodland, hedgerows and wetlands and cut the public off from accessing countryside in breach of Access Scotland legislation so from all points the salt marsh option seems the most valuable and economically viable
200	Nature will take its course. No matter what is planned nature will always find a way to defeat it. Better to find a way to stop building on flood plains and re build as required on higher ground. Also commercial interests and politics will influence the process and the pockets of the few in the know will be filled at the expense of the taxpayer. Each to his/her own defence I say.
204	The time we are present on earth represents a mere snapshot compared with the time the earth has been [and continues] evolving. Actions taken now to reduce coastal erosion can only expect to around 50 years at best. Natural forces will win ultimately.
205	The cost is important to me. I do not live in the locality so the impact on me directly is not so relevant YET I have several properties in Fife and could not support large increases in Council Tax.
208	A soft option would be preferable but there is a limit to what people can afford. If combined offers the best fiscal choice with the best coverage, that's my preference. I don't golf but I do have a personal farming interest. This influences my preference for what is protected.
212	I have said no change as I don't live in a flood plain and my house isn't in any danger of being flooded by any rivers nearby, so if people do want flood defences it should be them that pay extra council tax. and also I do not care that golf courses are in danger I do not play the game and it should be the courses owners that should pay for defences themselves as they bought the land next to a risk area.
216	I feel that property must be protected first and although I can see the tourism benefits of protecting St Andrews links feel this should be budgeted out of tourist taxes and business rates in tourist dependent business rather than council tax.

221	I do not believe that council tax should rise to pay for any future coastal defences. When the current wastage of money is considered, it becomes obvious that better use of financial resources by the council is the answer. The rash of pointless and ugly "traffic calming" measures which have recently defaced various towns and villages in NE Fife represents a colossal waste of tax payers' money. This is particularly galling when one considers the fact that these measures have been thoughtlessly altered or even removed again soon after (I use Tayport as a prime example). The council needs to look carefully at how it spends tax revenue, as the current situation is inexcusable. Secondly, I strongly believe St Andrews Links Trust should foot the bill for those defences which protect the golf courses. We have watched the trust grow into a very powerful and wealthy entity, which has immense financial resources and great influence. On the face of it, this may seem like a good thing; but the way the Trust has bullied local golfers has led many to question whether the Trust has lost sight of its initial remit, and the reasons for its inception. Put simply, if the Trust has the money to build another course that no one wanted (Castle), and in so doing ride roughshod over the wishes of local golfers; then it has the money to pay for coastal defences.
222	its a catch twenty two we want the best to protect everything and quickly but also naturally, but most people can't afford any more rises in anything so where do we go from here
232	I was looking for a natural/soft solution that would protect peoples' property.
237	Protection of property and farmland is obviously important, but within what is sustainable. I would weep no tears about golf courses disappearing. We are all impoverished by the demise of the wild environment so a predominantly salt marsh approach with minimal hard materials only to ensure protection of the most vulnerable properties makes sense to me.
248	Property has to be #1. Peoples lives and futures are the most important. Followed by farmland. If farming is halted food prices could rise thereby causing widespread economic problems. The more natural the type of defence used the better for the local eco system. Natural also blends in far quicker than hard defences would.
283	If it lowers insurance that I think it's worth paying extra
286	I don't think we should pay to protect the gold courses. Property, especially residential or school should take priority.
288	Why don't you just use farmland at risk for flooding - stock can be moved off when a serious flood warning and that way more money can be sent protecting property.
290	The natural option takes too long to be effective - we need a wall now. It won't matter what it looks like if our homes are protected
291	I don't like the look of the sea wall but I think it may be necessary in some locations as we need protection from flooding now. I wouldn't want it everywhere though. Could you paint it green to make it look better?
294	I don't think we should have to opt for one type of defence. It would be better if we could have a combination of them. Some places wouldn't look terrible with a sea wall such as built up places but others like farm land and parks would ruin them so a more natural approach would look better

300	We should be able to choose the type of defence dependent on whether it's property or farmland. Hard defences won't look as out of place by property and it is important to protect them sooner rather than later. Farmland should only have natural defences as it will blend better and is a more natural environment anyway

5.7 Discussion

With the risk of coastal flooding increasing due to climate change and the provision of coastal defences being costly, decisions related to coastal flood defences can be contentious, especially where limited resources are available. Understanding what the local communities' preferences and perceived values relating to coastal defences are can greatly assist managers such as those in the Eden estuary as to how to best utilise the resources available, particularly if the funds are from a public source.

5.7.1 Survey Respondents

The survey responses were mostly from the target area of north east Fife and were generally a good representation of age, sex and income from the region. Almost all the respondents had visited Tentsmuir National Park, the main recreational area bordering the Eden with over half of them visiting at least monthly. This suggests that most of the respondents had a familiarity with the Eden estuary and therefore are likely to be more invested in the survey.

There were ten respondents who opted for the *status quo* management scenario in all choice cards. Four of these respondents left open text comments which include the opinion that 'nature will take its course' and that building defences is considered futile in the long term. Three of the four also stated that they do not believe that council tax should pay for coastal defences as it should be the responsibility of the people at risk to defend their property. Whilst this is a clear viewpoint it appears to be held by a minority group of respondents. Over 60 % of the respondents never opted for the *status quo* scenario.

5.7.2 Model selection

The CLM was the poorest fitting model having the highest deviance. As all variables were fixed in this model, not allowing any variation between the respondents, this is not unexpected. The three MLM models fit the data more accurately with a smaller deviance when compared to the CLM but the significant variability in the beta values clearly demonstrated that there was a high amount of variability between the respondents' choices. The MLM model with random price was the best fitting of the models without interactions having the smallest deviance, however, significant variation in price between respondents was found. The addition of interacting the type of defence with the perception of risk accounted for some of the variation and was the best fitting model however there remained a large amount of unexplained heterogeneity in the respondents' choices.

Regardless of how well the three models without interactions fit the data, the same order of preference between the alternatives for type of coastal defence and type of land protected were found. The significance levels for these alternatives were also very similar across the three models. The model with the interaction indicated that the respondents' perception of being at risk of flooding accounted for some of the unexplained heterogeneity in the respondents' choices, improving the models fit.

5.7.3 Choice Experiment: Preferences for different types of coastal flood defence

Respondents demonstrated a preference for combined defences followed by soft defences and a dislike of hard defences. Including the respondents' perception of whether they are at risk from flooding, revealed that combined defences were the only scenario that held any utility. Furthermore, respondents who felt they were at risk from flooding had a higher preference for soft defences compared to those who did not believe their property to be at risk. This implies that the respondents trust that soft defences are capable of protecting their properties by defending the coast from flooding.

The preference for a more 'natural' form of engineering was also demonstrated when asking respondents about the factors that influenced their decisions, with habitat provision and aesthetics being more important than the initial and ongoing costs to the respondent. The time until the defence becomes an effective form of protection was rated the least important, however it was still rated as influential with two open comments stating their concern that soft defences would take too long to be effective.

Further evidence reflecting the preference for a more natural solution was provided in the open comments where some respondents stated that they felt the presence of a sea wall would ‘stand out’ and ‘marr’ the landscape, especially in rural settings. Respondents also commented that they did not believe that only one approach to coastal defence should be used and that a comprehensive review of the best type of defence given the risks for each location should be considered. This was not an option provided by the CE design as it was considered too cognitively demanding, however these responses demonstrate the importance the issue of flood defence to locals.

5.7.4 Choice experiment: Preferences to protect different types of land

With respect to the type of land to protect, unsurprisingly property was considered to have the highest priority, followed by farmland. Respondents opinions relating to protecting golf fairways were inconclusive.

The topic of what to protect using coastal defences appeared to be more contentious than that of the type of defence to use, with many open comments left relating to this topic. When selecting their preferred scenario, the type of land was not rated as the most important factor, however, it received the smallest number of least important ratings. This suggested that it was influential, if not the most important factor in the majority of the respondents’ decision making process.

Property was recognised as the preferred type of land to protect by all models, this was also apparent in the open text comments with eight respondents referencing the importance of protecting property as a priority. Some comments also raised the importance of protecting infrastructure such as the A91 which is only separated from the estuary by farmland. Comments relating to farmland were fewer and demonstrated mixed opinions with some viewing farmland as areas that should be allowed to flood to protect property and infrastructure. One comment did recognise the importance of farmland to the economy and therefore the importance of protecting it. The variation between respondents' choices relating to farmland and property was only minimally different.

The model estimation was inconclusive with respect to the preference of protecting golf courses. There was a significant unobserved heterogeneity in respondents' choices and plots of the distribution beta values indicated that most respondents were not strongly opposed paying to protect golf fairways, however there was a smaller group that strongly disliked the idea. The open comments reflected this with seven comments strongly opposing the use of public funds to protect golf courses, stating that there is enough wealth within the golfing private sector to be able to fund this. Approximately a quarter of the respondents identified themselves as golfers however there was only one comment that raised the importance of the golf courses to the area and recognised the importance of the Old Course above all others. By examining these comments and the distribution of the coefficient estimated by the models we can conclude that protecting golf courses had the lowest priority to the respondents with a strong thread that public funds should not be used for this.

5.7.5 Choice experiment: Willingness to Pay Values

Using the preferred MLM, mean WTP estimates for combined defences was £1195.53, for soft defences £729.21 and hard defences -£2207.87 per household. This is the total WTP per household and was proposed to be spread over a three-year period. The WTP estimates using the CLM model were less varied and had a lower range with combined defences being £892.15, soft defences £784.48 and for hard defences -£1757.38 per household over a three-year period. WTP estimates for coastal flood defences from this study exceed those presented in other studies completed in the UK (Table 5.14). Like other studies, a high degree of unexplained variation in the respondents choices was found (Brouwer *et al.*, 1999; Mangi *et al.*, 2011; Simpson and Hanley, 2016) with the respondents perception or experience of flood risk being found to be a positive driver for WTP for defences (Mangi *et al.*, 2011; Simpson and Hanley, 2016).

Table 5.14: Summary of willingness to pay (WTP) values from this study and others in the UK.

Type of coastal defence	Method	Mean WTP (£/household/year)			
		Hard Defences	Soft Defences	Combined Defences	Total
MLM with fixed price	CE	-735.96	243.07	398.51	-
CLM with fixed price	CE	-585.79	261.49	297.38	-
Mangi et al 2011	CV		213 (to preserve wetland)		-
Simpson & Hanley 2016	CV		42.79		-
Brouwer et al 1999	CV		83.65		-
Defra & English Nature 2005	Meta				150 - 200

Direct comparisons between studies is challenging due to the different survey methods and designs. The CV survey undertaken by Mangi et al (2011) provided the respondents with three management plans that were similar to the scenarios presented in this study. The management plans consisted of predominantly hard defences (75% hard, 25% wetland), predominantly soft defences (25% hard, 75% wetland) and combined defences (50% hard, 50% wetlands). The reported values for these scenarios were presented as the revenue generated from respondents WTP (number of households in area multiplies by the WTP). The combined defence management scenario received the highest WTP revenue (£10585) followed by the predominantly hard defence management scenario (£7833) with the soft defences management scenario receiving the least total revenue (£7092). Similar to this study, combined defences were the preferred option and the difference in the WTP between this and the other two alternatives (soft and hard) was much greater than the difference in WTP between soft and hard. Unlike this study, Mangi et al (2011) found a positive WTP for the predominantly hard scenario. Whilst we can't be certain of the reasons behind this difference the it is important to note that all of the scenarios in Mangi et al (2011) involved combined defences, solely hard defences were not offered which could explain the difference.

All the WTP estimates for combined and soft defences exceed the initial £600 maximum price level set for the pilot survey which would enable protection for the whole of the Eden estuary based on values calculated for engineering works (section 5.4.1). This suggests that respondents would be willing to accept and increase in their council tax to enable coastal protection for the whole Eden estuary to be enacted. Of the survey respondents, 24% believed that their property was at risk from coastal flooding. This is over four times (5.5%) the proportion of properties in the whole of Fife that are at risk (The Scottish Government, 2013; Angus Council, 2016). These respondents were found to have a greater preference for soft defences than respondents who do not perceive their property to be at risk from flooding. This could be explained by the preference observed for a more natural form of coastal defences given that these respondents perceive the threat of coastal flooding to be greater to them personally then it is likely they lived nearer the estuary. It also implies that respondents in the survey believe that soft defences can offer effective coastal flood defence and are not concerned by the length of time it would take for planted salt marshes to become effective coastal defences.

Many studies have demonstrated that the WTP for an improvement such as coastal flood defences decrease with the distance from the site (Jorgensen *et al.*, 2013; Simpson and Hanley, 2016). This was a point raised in the open comments by three respondents who stated that they were not at risk and therefore would not be willing to contribute and they believed that those at risk should be responsible. This suggests that the values may be an overestimate when considering the whole of Fife which is the area that the council tax increase presented would affect. However, it is important to note that respondents do value coastal flood defences and feel there is a need for them and are WTP.

The variation between respondents WTP for different flood defences clearly demonstrates that hard defences are disliked with both models providing a large negative estimate. This is important for managers to consider when developing coastal defence plans as proposing the use of hard defences is likely to meet high resistance compared to the use of combined or soft defences. Similarly, managers should consider the priority that respondents place on the importance of protecting property over farmland and the extreme opinions some hold with respect to protecting golf fairways. In the Eden Estuary, a partnership is already active between the local management authorities and stakeholders including representatives from the golf courses for funding coastal defences works. The continuation of this partnership is highly recommended based on the polar views observed within the respondents.

5.8 Conclusions

- Respondents demonstrated a preference for more natural engineering methods. Combined defences were the preferred option, followed by soft. The use of hard defences was disliked.
- Respondents demonstrated a preference to protect property and infrastructure over farmland. The use of public fund to protect golf fairways was met with some extremely negative views.
- Respondents were willing to pay for flood defences for property and farmland using combined or soft defences.
- The estimates for WTP should be used with consideration of the locality of the survey area to the survey site. An established relationship has been found in many studies of distance decay with WTP.
- High variability was seen between the respondents' preferences and WTP for coastal flood defences.
- The clear preference for certain types of coastal flood defence described above clearly illustrate the importance of stakeholder engagement when addressing contentious issues such as coastal flood defence. The preferences identified here provide useful information to managers and should be incorporated into any future coastal management plan.

Chapter 6: Discussion

The aim of this thesis was to improve our current understanding of the ability of a restored salt marsh to provide coastal flood defences, and the perceived value of this ecosystem service in such a role by the public. It employed ecological and economic methods, linking together the components of natural capital that underpin the ecosystem functions, which provide ecosystem services (ES), that contribute to human well-being. Interdisciplinary research, such as this case study, is important in light of the implementation of the ES framework which has been developed and become common place as a tool to manage our use of the environment and prevent further degradation (Secretariat of the Convention on Biological Diversity, 2005; UKNEA, 2014; Díaz *et al.*, 2015). The ES framework provides a basis by which the benefits, direct and indirect, that nature provides can be quantified, and monitored, in order to understand the impact in terms of losses and gains that a project or activity might yield to society and the environment. Underpinning our ability to effectively implement this framework is our knowledge of the links between the components of the ecosystem, the ecosystem functions they provide and how these contribute to the delivery of ecosystem services. In addition, our ability to develop and quantify measures for monitoring ecosystem functions that are representative of the provision of an ecosystem service and feasible in terms of physical monitoring is critical.

In the UK, salt marsh restoration, to provide or replace lost habitat and protect the coastline from flooding and erosion, has been practiced since the 1990s. Our knowledge of whether restored salt marshes provide the same suite of ecosystem functions and the length of time it takes for these to be restored is limited. In turn, this limits our knowledge of a restored salt marshes capacity to deliver ecosystem services and hinders decision making with respect to coastal planning strategies

The data presented in this thesis aid our understanding of:

- A restored salt marshes ability to provide equivalent protection from coastal flooding and erosion compared to that provided by a natural salt marsh, and the expected time it may take for this.
- The development of the benthic macrofaunal community in restored salt marshes.
- Public willingness to pay for coastal flood defences.
- Public preferences regarding different types of coastal defence and the type of land being protected.

Combining the findings from ecological and economic research in this thesis is unusual and enables insights that can assist in the planning of coastal flood defence providing valuable information to managers and policy makers.

6.1. Overview of Research Findings

6.1.1. Ecosystem Function in Restored Salt Marshes

Chapter 3 addressed the ability of the planted salt marshes in the Eden Estuary to attain equivalent ecosystem functioning to a natural salt marsh and consequently assess the capacity to deliver comparable coastal defence capabilities. The selection of the proxies used was based on an understanding of the ecosystem functions which contribute to coastal defence. Salt marshes provide effective coastal defences through their ability to attenuate and dissipate wave and tidal energy (Möller and Spencer, 2002; Pinsky, Guannel and Arkema, 2013; Möller *et al.*, 2014; Narayan *et al.*, 2016) , and trap and stabilise sediment, raising the height of the marsh and consequently keeping pace with sea level rise (Morris *et al.*, 2002; Crawford, 2008; Craft *et al.*, 2009).

Plant structure, monitored by means of height and density, were used as measures for a salt marshes' ability to attenuate wave energy and provided trajectories indicating the planted sites were likely to attain comparable ecosystem functioning to the natural salt marsh. The data suggested that after 10 years the planted sites would be able to attenuate and dissipate wave energy almost as effectively as the natural site. However due to the slower recovery of plant density compared to plant height there would still be a slight discrepancy in ecosystem function provision. Plant height had achieved equivalency 10 years after planting, whilst plant density appears to take longer with marginal but significant differences still present 11 years after planting. This estimated timeline was comparable with other studies (Garbutt *et al.*, 2006; Wolters *et al.*, 2008; Pétillon *et al.*, 2014; Brady and Boda, 2017).

This study was not able to establish any trajectory for sediment stability due to the high spatial and temporal natural variability in sediment characteristics. However, prior work completed in the Eden Estuary has established that the planted marshes were able to accrete sediment at a rate comparable to, or greater than, that of the natural salt marshes within four years of planting. This was assessed using short term sediment deposition and long term sediment accumulation as proxies (Maynard *et al.*, 2011; Maynard, 2014). This implies the ability of the planted salt marshes to deliver a comparable level of ecosystem function, trapping and stabilising sediment, is likely.

Considering the data from this study and the work completed by Maynard et al. (2011, 2014) the ability of the planted salt marshes to provide comparable levels of coastal defence from flooding and erosion is promising for the ongoing salt marsh restoration within the Eden Estuary. Some deficit in the ability of the planted salt marshes still exists 11 years after planting, however the expectation that equivalent capacity can be attained with sufficient time is high.

The identification and feasibility of suitable proxies to monitor ecosystem functions can be challenging. Where possible the selection of methods that can be easily replicated is advised to enable comparisons between studies. The proxies used in this study for monitoring plant structure and the method used by Maynard (2014) to monitor long-term sediment accumulation did not require any specialist equipment or training. This makes them ideal for monitoring a salt marshes' ability to provide coastal protection as they could be replicated in any location with minimal equipment costs. It is worth nothing that if the funds are available more technologically advanced methods, such as high-resolution mapping using lasers (Taylor, pers.comm.) are being trialled; these enable monitoring on a much larger scale.

6.1.2. Colonisation of the Benthic Macrofaunal Community in Restored Salt Marshes

Chapter 4 addressed whether the benthic macrofaunal community structure in the planted salt marshes is comparable to that of the natural stands. Monitoring the biodiversity of the macrofauna is an essential element of assessing the success of restoring salt marshes a clear link between biodiversity and ecosystem functioning has been demonstrated. Although the exact mechanisms behind this relationship may not be fully understood it is generally accepted that biodiversity underpins the provision of ecosystem services (Hooper *et al.*, 2005; Balvanera *et al.*, 2006; Worm *et al.*, 2006; Mangi *et al.*, 2011; Cardinale, 2012; Harrison *et al.*, 2014).

Benthic macrofaunal species richness was found to be comparable to that of a natural salt marsh 2 – 3 years after planting, however core abundance took longer to reach similar levels, only attaining comparable abundances to natural salt marsh 4 – 9 years after planting. Comparisons of community assemblage were more complex to interpret due to influences from variability in sediment characteristics and climate. Existing studies investigating the macrofaunal community in restored salt marshes are limited and have mixed findings, however we can cautiously conclude that sites restored through planting attain comparable levels of species richness earlier than sites restored through managed realignment (Garbutt *et al.*, 2006).

6.1.3. Valuation of Coastal Flood Defences in the Eden Estuary

Decisions related to coastal defences are often contentious within communities at risk from flooding. Limited public funds mean that the responsible body, which in Scotland are the local authority and SEPA, need to consider economic, social, environmental and physical factors when determining where and how to protect a particular area. Chapter 5 assessed public willingness to pay for coastal flood defences and the preferences regarding the type of defence employed and the kind of land protected. For decision makers, having information such as this can assist in designing coastal defence strategies.

This study found that the public do value coastal defences and are willing to pay towards their construction dependent on the type of defence used and what it is protecting. WTP estimates ranged between £243 and £398 per household per year (for a three year period) and exceeded those presented in other UK studies (Brouwer *et al.*, 1999; Mangi *et al.*, 2011; Simpson and Hanley, 2016). However, the preferences relating to the type of defences were consistent with other studies (Mangi *et al.*, 2011).

A clear preference for more “nature based” engineering methods was observed by the respondents in this research, with combined defences being the favoured option. This implies that the public have confidence in the ability of a salt marsh to protect the coast from flooding, however the added security of a sea wall provided a level of immediate protection. An aversion towards hard defences was apparent with respondents being concerned over their aesthetic image. Unsurprisingly, respondents prioritised the protection of property and infrastructure over farmland. There were some strong negative views concerning the use of public funds to protect golf courses. In the Eden Estuary, currently the golf courses do pay for their own coastal defences. In addition, they also actually contribute towards the funding that support the salt marsh restoration work which benefits the golf courses and the wider community, and this is not often recognised.

6.2. Wider Geographical Implications

The ability to extrapolate the findings from this study to other saltmarsh restoration projects both within the UK and further afield is currently limited due to the small scale and high variability within some of the data sets. Despite this the data, methods and conclusions still provide a valuable contribution for researches and practitioners due to the very limited data available.

Finding ‘model’ sites to monitor in the ‘real world’ and having the funds and ability to conduct a long-term monitoring project are challenging and consequently such data sets are not common. Sampling only occurred over a three year period for this study, however the ability to sample sites planted over a 10 year period simultaneously enabled models for greater than three years to be estimated. Whilst this was advantageous in ‘extending’ the time series modelled it introduced variation due to the different locations of the sites. Some of the high variability observed within the data, particularly the erosion threshold and to a lesser extent the macrofauna community, was due to the variation in sediment characteristics and water content present between sites. Spatial variation is well reported within the literature at meso to macro scales and therefore the high variability and low r-squared reported within this data is not surprising. Whilst the data for erosion thresholds and MPB community was inconclusive, the data for the macrofauna enables some conclusions to be made and provide vital data in an area where little data exists, thereby enhancing our understanding of restoration projects and development trajectories. The plant structure models had little unexplained variation and the estimated trajectories were comparable with other restoration projects worldwide.

The valuation of coastal flood defences estimated in this study was higher than in other studies, likely due to the high proportion of respondents feeling they were at risk from flooding and living relatively close to the Eden Estuary, both factors which are considered to potentially inflate values. There are currently very limited number of valuation studies due to the infancy of the field, the vast number of ES to value and the difficulty and cost in carrying out such a valuation. Methods are still being identified and developed to place quantifiable values on ES. The public’s preference for “nature based” defences and to protect property and infrastructure over farmland is a message that can be confidently transferred to other sites and provides practical advice for practitioners when designing flood defence schemes. Transferring the WTP values estimated in this study to other sites should only be carried out with a thorough understanding of the limitations of this study and the statistics used. Whilst the use of the WTP values estimated need to be handled with greater consideration, they still provide a much needed case study in a developing field where not many values exist.

6.3. Management Implications

The current UK flood management policy highlights the importance of implementing coastal defence strategies that are sustainable and 'adaptable in light of climate change' and incorporate stakeholder opinion (Defra, 2009). The results obtained from this study provide valuable information that can help decision makers in creating a coastal defence strategy. The findings not only provide an understanding of the length of time it would take for restored salt marshes to provide effective coastal defence but also offer insight into public preferences relating to coastal defences and the value placed on them.

Whilst it is accepted that salt marshes provide a sustainable form of coastal defence, evidence of whether restored salt marshes can deliver equivalent coastal defence to natural salt marshes is limited. This study concludes that restored salt marshes are capable of protecting the coast from flooding and provides an estimated period until restored salt marshes will be effective. This will enable decision makers to create a plan that can incorporate restoration alongside more immediate coastal defence measures for coastlines at imminent risk from flooding. In addition, this study provides information relating to the public opinions regarding coastal defences, both their preferred and, importantly, undesirable approaches. This assists greatly in designing coastal defence strategies in keeping with stakeholder engagement as required in the current UK Flood Management Strategy (Defra, 2009). This is especially true where public funds are being used and public disapproval could lead to objections over the implementation of such strategies. This study confirms that the public have confidence in soft engineering methods and these are less likely to be met with disapproval should they be proposed. It also suggests that should an increase in council tax, or similar fee be charged to assist in the payment for a coastal defence strategy, the public are likely to be accepting. However, it should be noted that an established relationship has been found in studies with the WTP for an improvement, such as coastal flood defence, decreasing with distance from the site (Jorgensen *et al.*, 2013; Simpson and Hanley, 2016). Those who do not perceive themselves to be at risk from coastal flooding may not be willing to contribute towards the cost.

In addition to information relating to the development of coastal defence planning, this study has provided some insights regarding selecting sites for salt marsh restoration and the development of monitoring strategies. The data indicated that sites that are located close to an existing salt marsh will be colonised more rapidly by benthic macrofauna than those at a greater distance. This should be taken into consideration when selecting sites to restore, as a very isolated site may take longer to develop the benthic macrofaunal community associated with salt marshes, or possibly fail altogether. The green alga, *Enteromorpha,* was found to have the potential to smother new shoots, inhibiting the development of higher plant densities. Whilst the evidence concerning this is not conclusive, it should be considered when selecting a site for restoration and clearance may be required for optimal response.

The data assessing the benthic macrofaunal community assemblage observed clearer distinctions between site assemblages at different times of the year. The summer had the most distinct assemblages, whilst the spring had the least. When designing monitoring strategies this should be considered, with sampling occurring at different times of year as well as annually where possible. Failure to do this could lead to erroneous conclusions of site equivalence.

6.4. Challenges of Interdisciplinary Research

Many of the components of the ES Framework are still poorly understood. Whilst many Governments and industries are starting to implement the ES Framework, researchers and academics are still trying to fully understand the foundations on which the conceptual model is based. Our understanding of how biodiversity and other components of the natural environment provide EFs and subsequently ES is limited, as is our ability to monitor changes in these and provide quantifiable values for ES. This is a challenging task and has led to the commissioning of many interdisciplinary projects from local to international levels that incorporate scientists, policy makers and practitioners. It is acknowledged that this type of interdisciplinary work is essential if we are to implement the ES approach, however conducting truly interdisciplinary research is challenging with many commenting of the research being multidisciplinary rather than interdisciplinary (Mace, Norris and Fitter, 2012; Balvanera *et al.*, 2014; UKNEA, 2014; Díaz *et al.*, 2015).

This study aimed to employ interdisciplinary research techniques, employing the ES framework, to improve the understanding of our ability to restore salt marshes and the ES value for coastal flood defence. Prior to starting this PhD, I had a background in ecology and very limited knowledge of environmental economics which initially led to a steep learning curve. Being able to converse with economists was challenging at the start due to the use of a plethora of unfamiliar abbreviations and terminology. I also found that some terms used in ecology had different meanings within economics. It is essential for this reason that when conducting interdisciplinary research that terms are defined early on to avoid wasted time any confusion at a later stage.

Another major challenge was being able to understand the statistical models used by another discipline. All disciplines seem to have their preferred software, some of which is costly and often require specialist training in the models utilised. A clear understanding of the modelling techniques to be used is important at the start of a project to ensure that the results from any survey designed can be analysed; this is commonplace across all disciplines (Louviere, Hensher and Swait, 2000; Zuur, Ieno and Elphick, 2010).

Whilst crossing into another discipline was a challenge I believe it has led to more practical and comprehensive data and conclusions. Combining my ecological knowledge of saltmarshes, advice from local managers with respect to potential coastal flood defence strategies with that of the economic modelling and design, made it possible to develop a more realistic scenario (incorporating combined defences).

Despite the challenges present in conducting interdisciplinary research I believe that it is essential if we are to improve our understanding of how best to implement the ES approach, provide ES valuations and therefore sustainably manage the environment.

6.5. Future Work

Whilst the data presented in this thesis is encouraging with respect to the likelihood of the younger planted sites within the Eden Estuary attaining comparable ecosystem functioning and capacity to protect the coast from flooding as the existing natural stands, continued monitoring is advisable. Plant density was not comparable to that of the natural stand after 11 years, continued monitoring would enhance our understanding of this trajectory. In addition, some of the younger planted sites are backed by a hard sea wall, and whilst currently there is no reason to expect this to inhibit restoration, continued monitoring would be important.

It was noted that for comparisons of macrofaunal community assemblage, the influences of differing sediment characteristics inhibited the ability to assess whether restoration was successful. Defining species within a community assemblage by the functional role that they exhibit is a method that is becoming increasingly popular when assessing biodiversity in terms of ecosystem functioning (TEEB, 2010); one such approach is biological traits analysis (BTA). BTA describes species in terms of their biological characteristics (or traits) such as life history, morphology and behaviour, that they exhibit (Bremner, 2008). It is these characteristics that describe the role, or function, that species perform within a community. More than one species is capable of fulfilling the same functional role, subsequently, where taxonomic differences are observed between assemblages, this may not equate to a functional difference. BTA incorporates abundance (or biomass) of species present within an assemblage, and their biological characteristics into the same analysis which enables comparison of the functional equivalency between assemblages (Bremner, 2008). Applying BTA to the benthic macrofaunal community data from this study may provide additional insights into the planted sites ability to provide comparable ecosystem functioning to the natural stands.

This study supports the careful restoration of salt marsh systems incorporating an ecosystem approach, and demonstrates that nature often has the capacity to provide the ecosystem service society requires. With careful management, this process can be enhanced and managed to the benefit of coastal communities.

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Appendix A

University of St Andrews University Teaching and Research Ethics Committee (UTREC) Approval.

29 August, 2013
Katherine Wade
Biology

Ethics Reference No: *Please quote this ref on all correspondence*	**BL10402**
Project Title:	**An Economic Valuation of Coastal Defence Management in the Eden Estuary using Contingent Valuation Methods**
Researchers Name(s):	**Katherine Wade**
Supervisor(s):	**Prof David Paterson**

Thank you for submitting your application which was considered at the Biology School Ethics Committee meeting on the 29 August 2013. The following documents were reviewed:

1. Ethical Application Form 26/07/2013
2. Other supporting documents 26/07/2013

The University Teaching and Research Ethics Committee (UTREC) approves this study from an ethical point of view. Please note that where approval is given by a School Ethics Committee that committee is part of UTREC and is delegated to act for UTREC.

Approval is given for three years. Projects, which have not commenced within two years of original approval, must be re-submitted to your School Ethics Committee.

You must inform your School Ethics Committee when the research has been completed. If you are unable to complete your research within the 3 three year validation period, you will be required to write to your School Ethics Committee and to UTREC (where approval was given by UTREC) to request an extension or you will need to re-apply.

Any serious adverse events or significant change which occurs in connection with this study and/or which may alter its ethical consideration, must be reported immediately to the School Ethics Committee, and an Ethical Amendment Form submitted where appropriate.

Approval is given on the understanding that the 'Guidelines for Ethical Research Practice' (http://www.st-andrews.ac.uk/media/UTRECguidelines%20Feb%2008.pdf) are adhered to.

Yours sincerely

Convenor of the School Ethics Committee OR Convener of UTREC

Ccs Prof David Paterson, Supervisor
School Ethics Committee

Appendix B

Script for information video used to provide background information for the choice experiment described in Chapter 5. A full copy of the video can be viewed online at https://www.youtube.com/watch?v=_0x396V9rqk&feature=youtu.be

Cover Slide

Thank you for agreeing to complete this survey.

Next Slide

This survey is part of a larger research project looking at the management of the Eden estuary located to the north of St Andrews and south of Dundee. We are interested in your opinions on the future coastal flood defence options within the Eden and your current use of the Eden.

Next Slide

Flooding has become an increasing concern over recent decades due to the predicted sea level rise and increase in extreme weather events. Coastal flooding occurs when the sea inundates the land. Extremely high tides, weather conditions and high rainfall in the catchment area, or a combination of these, can lead to coastal flooding.

Damage from flooding has high economic costs, damaging homes and businesses, and can be devastating at a personal level. Damage is not just restricted to property; it can also damage and disrupt transport networks which can prevent businesses from operating as normal, destroy crops and strand livestock. The impacts also have longer term influences in terms of clean up and increased insurance premiums.

Next Slide

Coastal flooding can occur for some distance inland of the actual coast. The green area on this map shows the area that is predicted to be as risk from coastal flooding and is estimated to be some 5 miles upstream of the mouth of the Eden.

To minimise damage and disruption caused by flooding, defences can be introduced or strengthened where already existing.

Next Slide

The local council is responsible for making decisions regarding the defences and paying for them. This means that the cost is generally passed onto households in the area, normally through council tax. It is therefore important that the options chosen are accepted by the general public.

Click

The council have limited resources so has to make decisions on the extent, location and type of defences to use. This survey gives you an opportunity to share your opinions. I will explain each of these factors in more detail. This information will be important in answering questions in the survey so please listen carefully.

Next Slide

EXTENT OF PROTECTION

The extent of protection refers to the length of coastline that is protected. This varies between zero% meaning no additional coastline is protected and 100% which means the entire coastline is protected.

Click

LOCATION OF PROTECTION

Due to the limited resources, it is unlikely that the entire coastline would be protected. Consequently, the protection offered by the construction of any future coastal flood defences will depend on where the defences are located.

Next Slide

In the Eden estuary approximately 50% of the coastline is bordered by property such as the houses, businesses and buildings in Guardbridge, Leuchars and St Andrews. The remaining 50% of coastline is nearly equally divided between farmland and golf courses.

This survey will not consider the coastline adjacent to Tenstmuir and West Sands as the management of these areas is already determined. We would like you to consider the remaining area of coastline between these two points, the majority of which consists of mudflats.

Next Slide

TYPE COASTAL DEFENCES

The different types of defences each have their own pros and cons. The three groups that you will be asked about in this survey are: natural/soft, hard/ manmade and combined – I will explain these in more detail now.

Next Slide

NATURAL (SOFT) DEFENCES

Natural, or soft defences, are those which use and expand upon the environments existing natural defence features. On the mudflats of the Eden saltmarshes can be used. They offer natural protection by absorbing wave energy and slowly accreting sediment which increases the height of the land adjacent to the coast. Once planted saltmarshes take at least 10 years until they can offer full coastal protection. Over this period, the protection they offer will increase progressively with the increased height and density of the plants.

Soft defences blend well with the natural environment as they do not substantially alter the way the landscape looks. They generally require little or no maintenance, cost nothing once established and provide additional habitat for wildlife, principally birds

Next Slide

HARD DEFENCES

In the Eden the most common type of hard defence are sea walls. Stone baskets such as those in these images of existing sea walls in the Eden are the most common material used locally. These aim to prevent erosion by absorbing and reflecting wave energy and raise the height of the coastline thereby preventing flooding.

Sea walls are relatively quick to install and offer immediate protection; however, they do alter the way the landscape looks quite dramatically. They have a limited lifetime of around 15-40 years and require on-going maintenance which has associated costs.

Next Slide

COMBINED

Combined defences use a combination hard and soft defence methods. In the Eden this will involve the building of a sea wall with saltmarsh in front of it. By combining these two types of defence the sea wall does not need to be as high as the saltmarsh in front will absorb some of the wave energy. This in turn means that the cost of maintenance is less, and life time of the wall is extended. Combined defences do offer some instant protection; however, this initial protection is not at full capacity as it will take 10 years for the saltmarsh to reach its full defence ability. Similar to soft defences the addition of saltmarshes offers extra habitat for wildlife.

Next Slide

SURVEY

You will now be asked a series of questions which will allow us to assess how you value and what your preferences are for the location of, extent of and type of defences to be used in future flood defence plans of the Eden.

First, you will be presented with a series of questions each of which consist of a table with (Click) 4 possible management options relating to future flood defence in the Eden. Each will have a cost associated with them (Click).

This cost is an estimate of how much your council tax may go up. The results of this survey could be used to inform future council policy, so your choices may influence the level of additional council tax you will be charged in future years. Please consider this carefully when answering the questions.

Of the four possible management options there will always be one for each of the three (Click) types of defence explained earlier. Each of these will have an increase in council tax associated with them. These will vary in the extent of protection (Click) offered and what type of land will be protected. The fourth management (Click) option will be for no change which means that there will be no additional coastal flood defences built and will have no increase in council tax associated with it.

Please consider each of the four options available at each question and select the one you like best by checking the box.

There are no right or wrong answers; we are just interested in your opinion. If you think the cost of a choice is too expensive or that you could not afford it or you feel that the money could be better spent elsewhere please choose the ‘no change’ option.

Following these questions, you will be asked why you chose the options you did in this first section of the survey. These will then be followed by some general questions about you and your household.

LINK DIRECTLY TO SURVEY

Appendix C

Hard copy of the CE survey used in chapter 5 to assess willingness to pay for coastal flood defences in the Eden Estuary. The survey was completed online using software developed by SurveyGizmo.

University of St Andrews

University Teaching and Research Ethics Committee

29 August, 2013
Katherine Wade
Biology

Ethics Reference No: *Please quote this ref on all correspondence*	**BL10402**
Project Title:	**An Economic Valuation of Coastal Defence Management in the Eden Estuary using Contingent Valuation Methods**
Researchers Name(s):	**Katherine Wade**
Supervisor(s):	**Prof David Paterson**

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Approval is given on the understanding that the 'Guidelines for Ethical Research Practice' (http://www.st-andrews.ac.uk/media/UTRECguidelines%20Feb%2008.pdf) are adhered to.

Yours sincerely

W. Anne Smith

Convenor of the School Ethics Committee OR Convener of UTREC

Ccs

Prof David Paterson, Supervisor
School Ethics Committee

Eden Coastal Flood Defence Survey

Consent Page

Page description:

ID 152

Thank you for agreeing to participate in this survey. This survey has been produced as part of a research project carried out and funded by the University of St Andrews, University of Stirling and the Marine Alliance for Science and Technology for Scotland (MASTS).

ID 153

Before you begin please ensure that you have read and agree to the information provided on the 'Privacy Information' page of the website. All information you provide will be remain anonymous, confidential and will be stored securely.

- I confirm that I have read and agree to the information provided on the 'privacy information' page of the website.
- I DO NOT agree to the information provided on the 'privacy information' page of the website.

ID 154

The data collected will be used to publish scientific papers. Any outcomes will also be shared with Fife Council. If you wish to end the survey at any point please just close the window.

ID 155

Page exit logic: Disqualification if consent not given
IF: Question "Before you begin please ensure that you have read and agree to the information provided on the 'Privacy Information' page of the website. All information you provide will be remain anonymous, confidential and will be stored securely." is one of the following answers ("I DO NOT agree to the information provided on the 'privacy information' page of the website.") **THEN:** Disqualify and display:
We require you to agree to the privacy information on the website in order for you to participate. If you have any questions relating to this please do not hesitate to get in contact with us. Contact details can be found on the website. Thank you for your interest in the survey. Please close the window to exit.

Info Video

Page description:

ID 138

Please watch the video below. This will provide you with some important information you will need to answer the survey.
You can enlarge the video by selecting the icon on the bottom right of the image.

Hard/Soft Comparison Slider

Page description:

Action: Percent Branch

Choice Card Branches

VALIDATION Min = -100 Max = 100

DATA Shortname / Alias: **Hard/Soft Slider**

ID 2

Do you have a preference for natural/soft or man-made/hard defences?

If you would prefer 100% of coastal defence in the Eden to consist of only one of these options that move the slider to the end of the line with that label.

100% Natural/soft	50:50	100% Manmade / Hard

ID 3

Natural / Soft Defences e.g. saltmarsh planting	**Manmade / Hard Defences** e.g. sea wall
• Progressive protection (10 years)	• Instant protection
• Sustainable	• Lifetime of 15-40
• No on going cost	• On going maintenance cost
• Blends well with the natural environment	• Dramatic change to the way the landscape looks
• Additional habitat for wildlife	• No additional habitat for wildlife

Block 1 Card 1

Page description:

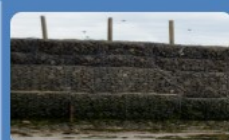
ID 53

You will now be asked to answer 8 management scenario questions. These may appear repetitive but each question has a scenario with different levels of coastal protection. These will allow us to understand which aspects of coastal flood protection are important to you and how much you are willing to pay based on these preferences.

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 52

Type of land to be protected by coastal defences:	Future Management Options  Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **30%** of coastline	Protect **10%** of coastline	Protect **30%** of coastline	Protect **0%** of coastline
 Farmland	Protect **0%** of coastline	Protect **25%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **10%** of coastline	Protect **20%** of coastline	Protect **5%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£225**	**£40**	**£300**	**£0**

Card 1 of 8

Block 1 Card 1 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 1 Card 2

Page description:

ID 55

Please select your preferred management option *

Natural/Soft ◯ | Manmade/Hard ◯ | Combined ◯ | No Change ◯

ID 56

Type of land to be protected by coastal defences:	Future Management Options  Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **10%** of coastline	Protect **20%** of coastline	Protect **50%** of coastline	Protect **0%** of coastline
 Farmland	Protect **25%** of coastline	Protect **15%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **20%** of coastline	Protect **10%** of coastline	Protect **5%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£120**	**£300**	**£40**	**£0**

Card 2 of 8

Block 1 Card 2 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 1 Card 3

Page description:

ID 57

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 63

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **40%** of coastline	Protect **30%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline
 Farmland	Protect **5%** of coastline	Protect **5%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **5%** of coastline	Protect **25%** of coastline	Protect **5%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£120**	**£120**	**£120**	**£0**

Card 3 of 8

Block 1 Card 3 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 1 Card 4

Page description:

ID 58

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 64

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **20%** of coastline	Protect **20%** of coastline	Protect **30%** of coastline	Protect **0%** of coastline
 Farmland	Protect **0%** of coastline	Protect **15%** of coastline	Protect **25%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **15%** of coastline	Protect **0%** of coastline	Protect **25%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£225**	**£225**	**£40**	**£0**

Card 4 of 8

Block 1 Card 4 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 1 Card 5

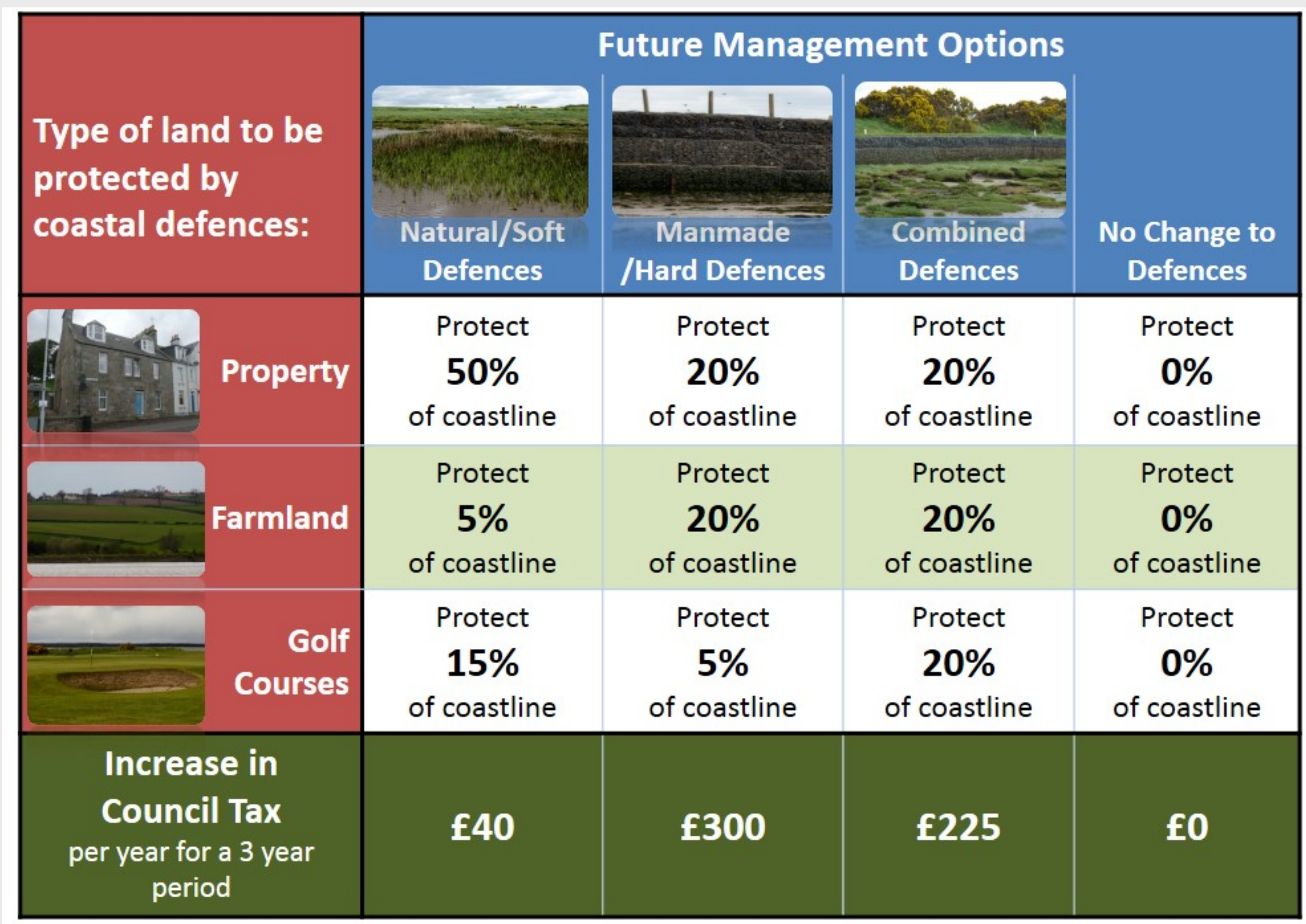
Page description:

ID 59

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 65



Type of land to be protected by coastal defences:	Future Management Options: Natural/Soft Defences	Manmade /Hard Defences	Combined Defences	No Change to Defences
Property	Protect **50%** of coastline	Protect **20%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline
Farmland	Protect **5%** of coastline	Protect **20%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline
Golf Courses	Protect **15%** of coastline	Protect **5%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£40**	**£300**	**£225**	**£0**

Card 5 of 8

Block 1 Card 5 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

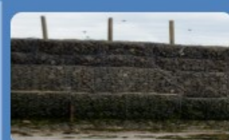
Block 1 Card 6

Page description:

ID 60
Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 66

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **40%** of coastline	Protect **30%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
 Farmland	Protect **15%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **25%** of coastline	Protect **0%** of coastline	Protect **15%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£175**	**£175**	**£75**	**£0**

Card 6 of 8

Block 1 Card 6 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

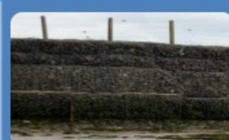
Block 1 Card 7

Page description:

ID 61
Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 67

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **0%** of coastline	Protect **50%** of coastline	Protect **30%** of coastline	Protect **0%** of coastline
 Farmland	Protect **25%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **20%** of coastline	Protect **10%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£40**	**£225**	**£225**	**£0**

Card 7 of 8

Block 1 Card 7 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 1 Card 8

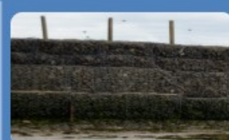
Page description:

ID 62

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 68

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **10%** of coastline	Protect **40%** of coastline	Protect **30%** of coastline	Protect **0%** of coastline
 Farmland	Protect **20%** of coastline	Protect **5%** of coastline	Protect **15%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **0%** of coastline	Protect **25%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£75**	**£120**	**£300**	**£0**

Card 8 of 8

Block 1 Card 8 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 2 Card 1

Page description:

ID 69
You will now be asked to answer 8 management scenario questions. These may appear repetative but each question has scenarios that differ. These will allow us to understand which aspects of coastal flood protection are important to you and how much you are willing to pay based on these preferences.

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 70

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **40%** of coastline	Protect **30%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline
 Farmland	Protect **25%** of coastline	Protect **0%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **10%** of coastline	Protect **25%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£175**	**£75**	**£120**	**£0**

Card 1 of 8

Block 2 Card 1 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 2 Card 2

Page description:

ID 71

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 72

Type of land to be protected by coastal defences:	Future Management Options  Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **50%** of coastline	Protect **30%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
 Farmland	Protect **15%** of coastline	Protect **20%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **0%** of coastline	Protect **15%** of coastline	Protect **25%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£75**	**£300**	**£75**	**£0**

Card 2 of 8

Block 2 Card 2 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 2 Card 3

Page description:

ID 73

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 74

Type of land to be protected by coastal defences:	Future Management Options:  Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 **Property**	Protect **0%** of coastline	Protect **20%** of coastline	Protect **50%** of coastline	Protect **0%** of coastline
 **Farmland**	Protect **15%** of coastline	Protect **5%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline
 **Golf Courses**	Protect **10%** of coastline	Protect **20%** of coastline	Protect **15%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£120**	**£175**	**£120**	**£0**

Card 3 of 8

Block 2 Card 3 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 2 Card 4

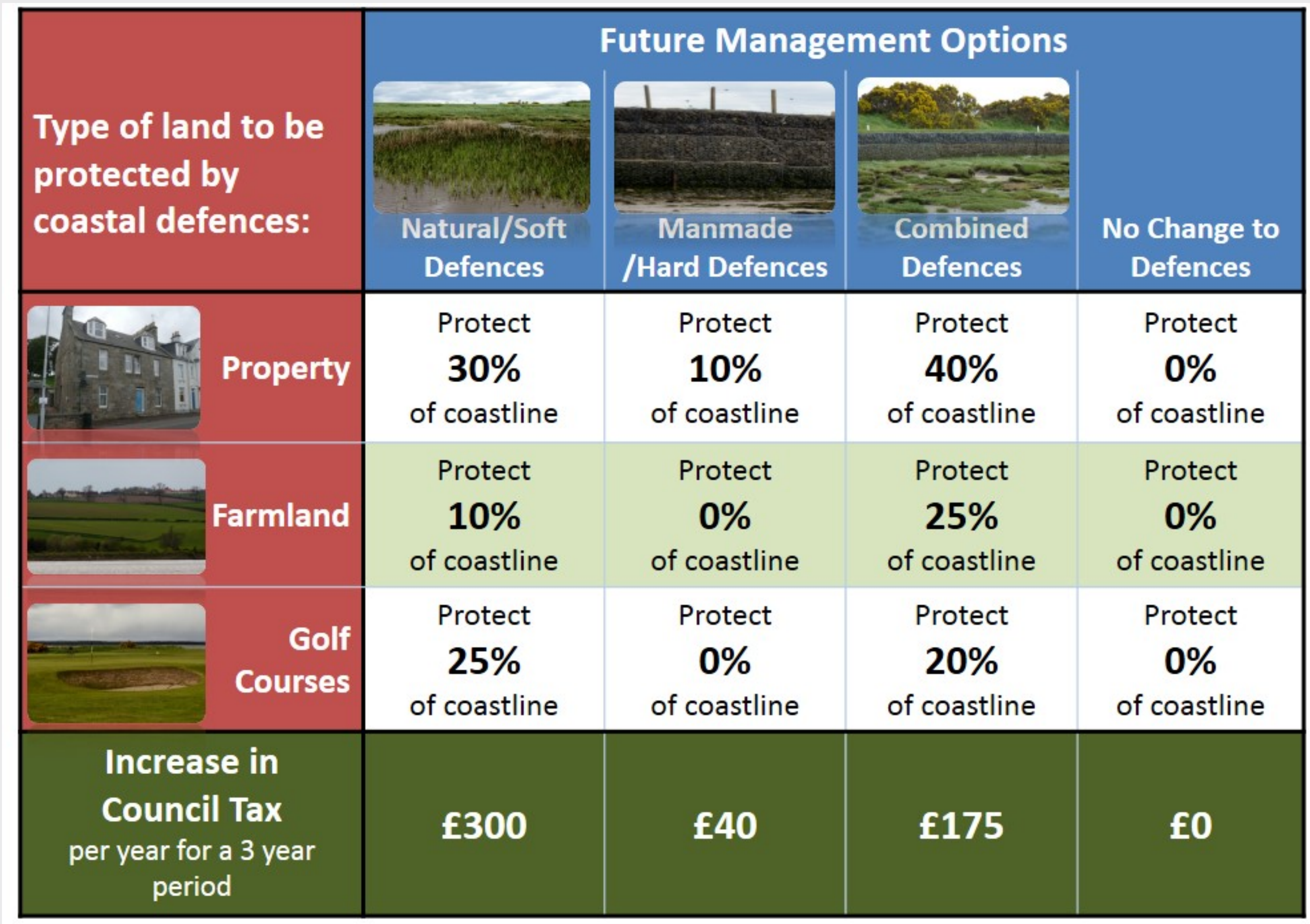
Page description:

ID 75

Please select your preferred management option *

Natural/Soft ○ Manmade/Hard ○ Combined ○ No Change ○

ID 76



Type of land to be protected by coastal defences:	Natural/Soft Defences	Manmade /Hard Defences	Combined Defences	No Change to Defences
	Future Management Options			
Property	Protect **30%** of coastline	Protect **10%** of coastline	Protect **40%** of coastline	Protect **0%** of coastline
Farmland	Protect **10%** of coastline	Protect **0%** of coastline	Protect **25%** of coastline	Protect **0%** of coastline
Golf Courses	Protect **25%** of coastline	Protect **0%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£300**	**£40**	**£175**	**£0**

Card 4 of 8

Block 2 Card 4 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 2 Card 5

Page description:

ID 77

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 78

Type of land to be protected by coastal defences:	Future Management Options: Natural/Soft Defences	Manmade /Hard Defences	Combined Defences	No Change to Defences
Property	Protect **20%** of coastline	Protect **40%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
Farmland	Protect **15%** of coastline	Protect **20%** of coastline	Protect **5%** of coastline	Protect **0%** of coastline
Golf Courses	Protect **5%** of coastline	Protect **0%** of coastline	Protect **25%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£300**	**£120**	**£75**	**£0**

Card 5 of 8

Block 2 Card 5 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 2 Card 6

Page description:

ID 79

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 80

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **10%** of coastline	Protect **40%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
 Farmland	Protect **0%** of coastline	Protect **25%** of coastline	Protect **5%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **20%** of coastline	Protect **15%** of coastline	Protect **5%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£175**	**£40**	**£175**	**£0**

Card 6 of 8

Block 2 Card 6 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 2 Card 7

Page description:

ID 81

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 82

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **40%** of coastline	Protect **0%** of coastline	Protect **40%** of coastline	Protect **0%** of coastline
 Farmland	Protect **20%** of coastline	Protect **0%** of coastline	Protect **15%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **25%** of coastline	Protect **10%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£175**	**£40**	**£300**	**£0**

Card 7 of 8

Block 2 Card 7 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

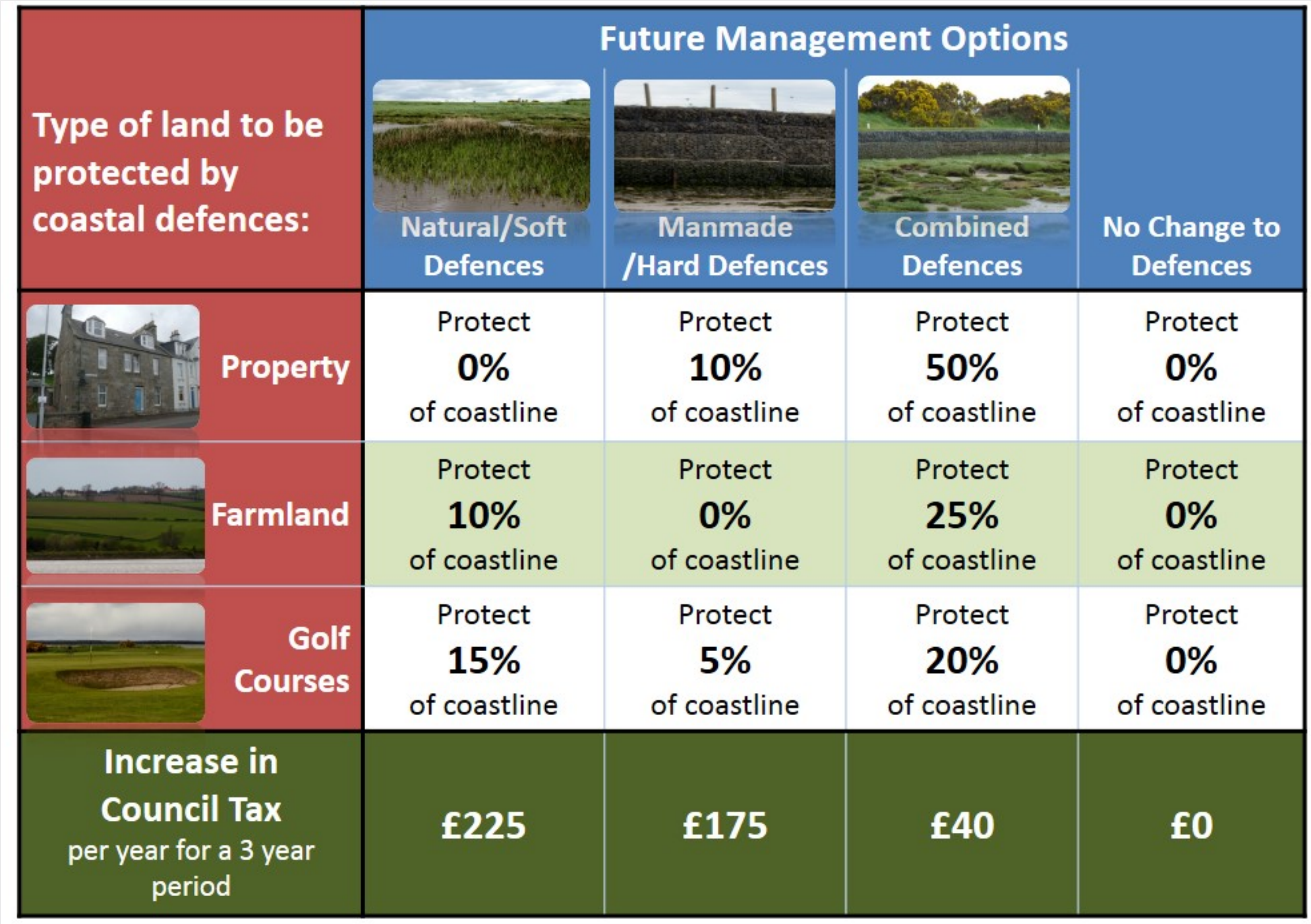
Block 2 Card 8

Page description:

ID 83
Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 84



Type of land to be protected by coastal defences:	Future Management Options: Natural/Soft Defences	Manmade /Hard Defences	Combined Defences	No Change to Defences
Property	Protect **0%** of coastline	Protect **10%** of coastline	Protect **50%** of coastline	Protect **0%** of coastline
Farmland	Protect **10%** of coastline	Protect **0%** of coastline	Protect **25%** of coastline	Protect **0%** of coastline
Golf Courses	Protect **15%** of coastline	Protect **5%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£225**	**£175**	**£40**	**£0**

Card 8 of 8

Block 2 Card 8 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 3 Card 1

Page description:

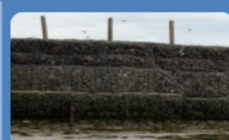
ID 85

You will now be asked to answer 8 management scenario questions. These may appear repetative but each question has scenarios that differ. These will allow us to understand which aspects of coastal flood protection are important to you and how much you are willing to pay based on these preferences.

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 86

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **10%** of coastline	Protect **50%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
 Farmland	Protect **15%** of coastline	Protect **10%** of coastline	Protect **5%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **5%** of coastline	Protect **25%** of coastline	Protect **15%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£120**	**£75**	**£225**	**£0**

Card 1 of 8

Block 3 Card 1 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 3 Card 2

Page description:

ID 87

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 88

Type of land to be protected by coastal defences:	Future Management Options:  Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **30%** of coastline	Protect **40%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline
 Farmland	Protect **5%** of coastline	Protect **25%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **0%** of coastline	Protect **20%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£75**	**£120**	**£225**	**£0**

Card 2 of 8

Block 3 Card 2 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 3 Card 3

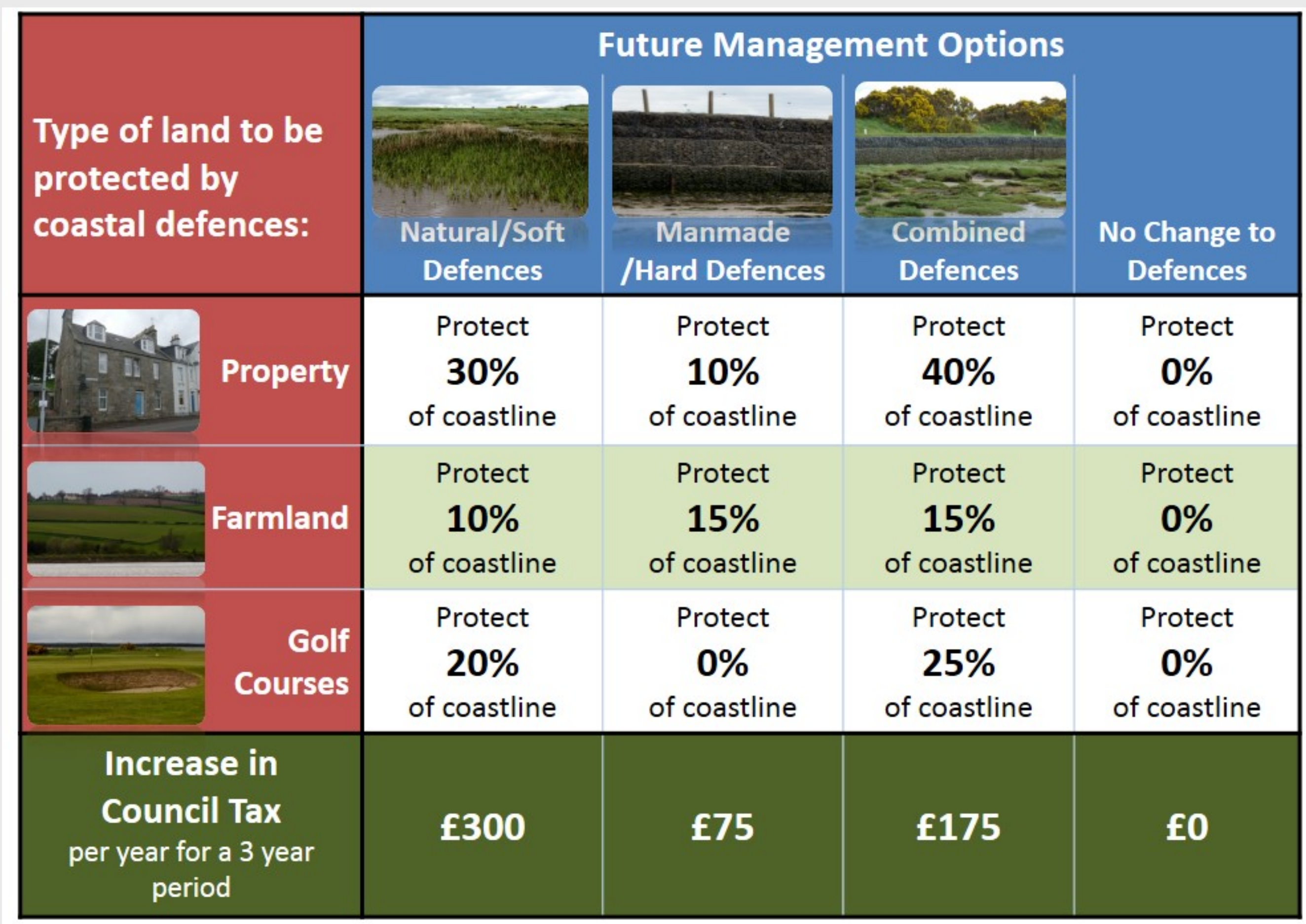
Page description:

ID 89

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 90



Type of land to be protected by coastal defences:	Future Management Options: Natural/Soft Defences	Manmade /Hard Defences	Combined Defences	No Change to Defences
Property	Protect **30%** of coastline	Protect **10%** of coastline	Protect **40%** of coastline	Protect **0%** of coastline
Farmland	Protect **10%** of coastline	Protect **15%** of coastline	Protect **15%** of coastline	Protect **0%** of coastline
Golf Courses	Protect **20%** of coastline	Protect **0%** of coastline	Protect **25%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£300**	**£75**	**£175**	**£0**

Card 3 of 8

Block 3 card 3 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 3 Card 4

Page description:

ID 91
Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 92

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **0%** of coastline	Protect **50%** of coastline	Protect **30%** of coastline	Protect **0%** of coastline
 Farmland	Protect **20%** of coastline	Protect **10%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **20%** of coastline	Protect **5%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£40**	**£175**	**£300**	**£0**

Card 4 of 8

Block 3 Card 4 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 3 Card 5

Page description:

ID 93

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 94

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **20%** of coastline	Protect **50%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline
 Farmland	Protect **5%** of coastline	Protect **15%** of coastline	Protect **15%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **25%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£75**	**£225**	**£120**	**£0**

Card 5 of 8

Block 3 Card 5 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 3 Card 6

Page description:

ID 95

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 96

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **10%** of coastline	Protect **0%** of coastline	Protect **50%** of coastline	Protect **0%** of coastline
 Farmland	Protect **10%** of coastline	Protect **25%** of coastline	Protect **0%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **10%** of coastline	Protect **5%** of coastline	Protect **25%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£300**	**£75**	**£75**	**£0**

Card 6 of 8

Block 3 Card 6 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

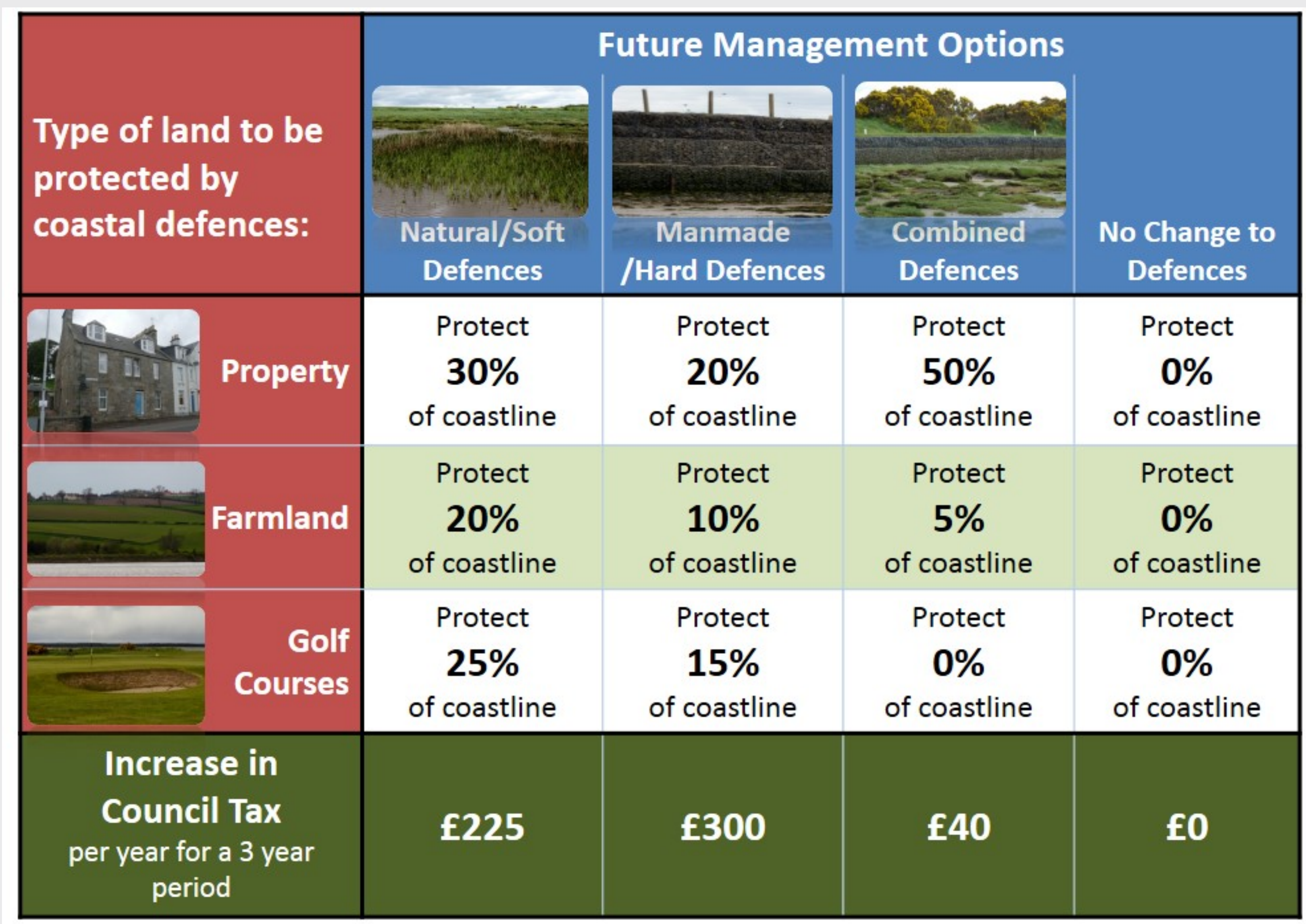
Block 3 Card 7

Page description:

ID 99
Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 100



Type of land to be protected by coastal defences:	Future Management Options: Natural/Soft Defences	Manmade /Hard Defences	Combined Defences	No Change to Defences
Property	Protect 30% of coastline	Protect 20% of coastline	Protect 50% of coastline	Protect 0% of coastline
Farmland	Protect 20% of coastline	Protect 10% of coastline	Protect 5% of coastline	Protect 0% of coastline
Golf Courses	Protect 25% of coastline	Protect 15% of coastline	Protect 0% of coastline	Protect 0% of coastline
Increase in Council Tax per year for a 3 year period	£225	£300	£40	£0

Card 7 of 8

Block 3 Card 7 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Block 3 Card 8

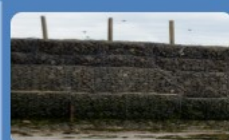
Page description:

ID 97

Please select your preferred management option *

Natural/Soft	Manmade/Hard	Combined	No Change
○	○	○	○

ID 98

Type of land to be protected by coastal defences:	Future Management Options			
	 Natural/Soft Defences	 Manmade /Hard Defences	 Combined Defences	No Change to Defences
 Property	Protect **50%** of coastline	Protect **0%** of coastline	Protect **20%** of coastline	Protect **0%** of coastline
 Farmland	Protect **0%** of coastline	Protect **5%** of coastline	Protect **25%** of coastline	Protect **0%** of coastline
 Golf Courses	Protect **15%** of coastline	Protect **15%** of coastline	Protect **10%** of coastline	Protect **0%** of coastline
Increase in Council Tax per year for a 3 year period	**£40**	**£225**	**£175**	**£0**

Card 8 of 8

Block 3 Card 8 Time **Action: Hidden Value**
Value: Populates with the **length of time** since the survey taker started the current page

Factors affecting decisions

Page description:

ID 6

How important are the following factors when deciding which type of coastal defence options you would like to be used (natural/soft, manmade/hard, combined)?

	unimportant	somewhat unimportant	neither important or unimportant	somewhat important	very important
Provision of habitat for wildlife *	○	○	○	○	○
Cost of on-going maintenance *	○	○	○	○	○
Time until defence is effective *	○	○	○	○	○
What it looks like/aesthetics *	○	○	○	○	○
Initial cost of defence to you *	○	○	○	○	○

ID 12

When you were choosing your preferred management scenario, how important were the following factors in your decision?

Please drag and drop the most important factor to the top of the list, and the least important at the bottom.

Drag items from the left-hand list into the right-hand list to order them.

- The extent of defence planned
- Type of coastal defence used
- What is being protected by the defence
- The cost of the defence to you

ID 102

Please add any additional comments relating to your choices below. If you opted for the 'no change' option we would be particularly interested to hear why.

Interests & Use of the Eden

Page description:

ID 13

How often do you visit/use the following places?

	Daily	Weekly	Monthly	Less often	Never
Tentsmuir Nature Park (including Morton Lochs)	○	○	○	○	○
The Eden Centre	○	○	○	○	○
Bird hides around the Eden and Tentsmuir	○	○	○	○	○

ID 19

Are you a member of any conservation groups (e.g. RSPB, The Wildlife Trust, National Trust, WWF)?

- ○ Yes
- ○ No
- ○ Prefer not to say

ID 187

1. Do you work in the coastal environment sector?

- ○ Yes
- ○ No
- ○ Prefer not to say

ID 24

Do you participate in the following activities?

	Yes	No	Prefer not to say
Golf	○	○	○
Wildfowling	○	○	○
Birdwatching	○	○	○

ID 197

2. Do you believe that the results of this survey will be shared with policy makers?

- ○ Yes
- ○ No
- ○ Prefer not to say

Personal Information

Page description:

ID 48

We will now ask you some questions about you and your household. We understand that your privacy is important to you and that you may not be keen to disclose personal information. The questions we are asking are important to this study for the the following reasons:

- They enable us to gauge whether the participants are representative of the general population, or whether there is any bias, such as the majority being below 30 years old.
- Household salary is particularly important information. One of the key outcomes of the survey is to estimate how much people would be willing to pay for different coastal flood defence management options. This will be calculated from the management scenario questions you answered earlier. Your household income is likely to have been an influential factor in determining the choices you made.

Please be assured that all information you provide is **anonymous, confidential** and will be **stored securely.**

ID 34

Are you?

- ○ Male
- ○ Female
- ○ Prefer not to say

ID 35

What age are you?

- under 18
- 18-21
- 22-24
- 25-34
- 35-44
- 45-54
- 55-64
- 65+
- Prefer not to say

ID 33

How would you describe your current employment status?

- Full time employee (35+hours/ week)
- Part time employee (less than 35 hours/week)
- Stay at home parent
- Part time student
- Full time student
- Retired
- Unemployed
- Prefer not to say
- Self employed

Household Info 1

Page description:

ID 37

What is your postcode?

Please reveal as much of your postcode as you are happy to. A full postcode does not identify an individual house but around 15 to 30 properties. Your postcode is required for us calculate your distance from the Eden estuary and to see where we have collected data from.

ID 186

3. **What town do you live in?**

If do not live in a town please state the nearest one to you.

ID 38

How would you describe your status in this property?

- Owner
- Rent from a private landlord or letting agent
- Rent from a council authority
- Live rent free in the property
- Other

ID 39

Do you think this property is at risk from flooding?

- Yes
- No
- Don't know

Household Info 2

Page description:

ID 41

Do you share this property with any other person?

- Yes
- No
- Prefer not to say

ID 42

If yes, please specify the number of sharers in each category:

	Number of people
16 and under	
16 - 17 years	
18 - 65 years	
65 + years	

ID 36

What is the approximate total gross annual income (before tax) for your household?

This information is anonymous and confidential and is key to assessing how you value the possible future coastal defence options in the Eden.

- Under £10,000
- £10,000 - £14,999
- £15,000 - £19,999
- £20,000 - £24,999
- £25,000 - £29,999
- £30,000 - £39,999
- £40,000 - £49,999
- £50,000 - £69,999
- Over £70,000
- Prefer not to say

ID 156

Did you participate in the pilot study which took place from 1st September to 30th October 2013?

- Yes
- No

ID 188

4. How did you hear about the survey?

- Word of mouth
- Internet
- E-mail
- Post
- At an event
- Press
- Other

Prize Draw Entry

Page description:

Page exit logic: Page Logic
IF: Question "Would you like to enter the prize draw?
Please note your contact details will be stored in a separate database to those from the earlier questions. This will ensure that your responses remain anonymous." #5 is one of the following answers ("No") **THEN:** Jump to page 34 - Thank You! Flag response as complete

Page exit logic: Prize Draw Entry Logic
IF: Question "Would you like to enter the prize draw?
Please note your contact details will be stored in a separate database to those from the earlier questions. This will ensure that your responses remain anonymous." #5 is one of the following answers ("Yes") **THEN:** Flag response as complete Redirect to:
www.surveygizmo.com/s3/1912998/Eden-Survey-Prize-Draw

Page exit logic: Prize draw No Entry Logic
IF: Question "Would you like to enter the prize draw?
Please note your contact details will be stored in a separate database to those from the earlier questions. This will ensure that your responses remain anonymous." #5 is one of the following answers ("No") **THEN:** Jump to page 34 - Thank You!

Page exit logic: Prize Draw Entry Logic
IF: Question "Would you like to enter the prize draw?
Please note your contact details will be stored in a separate database to those from the earlier questions. This will ensure that your responses remain anonymous." #5 is one of the following answers ("Yes") **THEN:** Flag response as complete Redirect to: www.surveygizmo.com/s3/1912998/Eden-Survey-Prize-Draw

ID 200

Thank you for completing the survey. We value your responses highly.

As a thank you for completing the survey we would like to invite you to enter a prize draw. The prizes include Amazon vouchers of the following denominations: 1 x £50, 2 x £25, 3 x £10.

ID 201

5. Would you like to enter the prize draw?
Please note your contact details will be stored in a separate database to those from the earlier questions. This will ensure that your responses remain anonymous.

- Yes
- No

ID 206

Thank You!

198

Thank you for completing the survey. We value your responses highly.
If you have friends or family who live in Fife and would be interested in completing the survey please forward the link to them.

For more information about the survey or to contact us please refer to the website.
You will now be re-directed to the website.

Action: URL Redirect

You will now be redirected to the website

137

University of St Andrews

UNIVERSITY OF STIRLING

Marine Alliance Science Technology Scotland