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Ecosystem functioning, goods and services in the coastal environment

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Reviewed by:

Name: Megan Stewart

Position: Project Leader – Marine

Organisation: ARC

Date: 30 July 2010

Approved for ARC Publication by:

Name: Grant Barnes

Position: Group Manager, Monitoring and Research

Organisation: ARC

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Ecosystem functioning, goods and services in the coastal environment

Michael Townsend
Simon Thrush

Prepared for
Auckland Regional Council

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road, Hamilton
PO Box 11-115, Hamilton, New Zealand
Phone +64-7-856 7026, Fax +64-7-856 0151
www.niwa.co.nz

Contents

Reviewed by:

Dr Judi Hewitt

Approved for release by:

Dr Drew Lohrer

Formatting checked

A. Bartley

1 Executive Summary

Auckland has a vast array of coastal ecosystems that provide many benefits to residents. Coastal ecosystems produce not only goods, such as fish and shellfish, and amenity and recreational values but in addition provide a number of important services that play crucial roles in supporting human, plant and animal populations. For example nutrient cycling, contaminant sequestration, flood control, coastal protection and resilience to disturbance are all of intrinsic human benefit.

Often these ecosystem goods and services are either not recognised or are excluded from the decision-making process because markets fail to reflect their economic value. Most ecosystem services are provided free, that is, they do not have to be purchased and we take them for granted. It is only when these services are lost that actual monetary costs are incurred. Since it is rare for an individual owner to receive direct monetary gains for benefits that an ecosystem provides for other users (e.g., downstream water quality), the value of such benefits is not generally taken into account in land use or coastal resource exploitation decisions. Failure to incorporate these hidden benefits and recognise multiple values can lead to management decisions being made where the final costs outweigh the short-term benefits to a small sector of society.

It is now generally accepted that environmental benefits do have real economic value and that these values must be included in decision-making processes. ARC commissioned the Cawthron Institute to develop a value estimation framework using discrete choice modelling (DCM: Batstone and Sinner 2010). The DCM provides a vehicle to understand Aucklander's coastal preferences and the economic benefits that flow from mitigation expenditure; however, it only incorporates a 'notion' of ecological health, without explicitly defining the components that define health from an ecological viewpoint. The current report supports economic valuation frameworks by providing a sound understanding of how ecosystems provide goods and services and the processes involved with their generation. Once recognised these goods and services can then be incorporated in to various assessment models, including the DCM. The report aims to increase the general understanding of the goods and services that estuarine and coastal ecological systems provide, by answering the following questions:

- What is the full range of ecosystem goods and services that humans rely on and which of these are provided in the Auckland coastal environment (section 3)?
- How do ecosystem functions underpin these services and affect their regulation and delivery (section 4)?
- How do these functions and services vary in space and time and what are the implications of anthropogenic disturbance on future delivery (section 5)?

Ecosystem goods and services in coastal environments can be divided into four major categories: Provisioning, regulating, supporting and cultural services, all of which can further be divided into 17 separate categories. To link goods and services to the underpinning ecological functions a 'general principle' approach was developed which avoided the overwhelming complexity of incorporating all known ecological information. Generally accepted ecological principles were used to make connections between ecosystem functions and goods and services in a way that is meaningful and relevant at a regional ecosystem management level. The principle approach suggests that for Waitemata Harbour:

- Maintaining productivity in all trophic levels is central to all service provisioning. Productivity not only (directly) supplies food and raw materials, but is the source of material and energy that flows through ecosystems and is connected to all regulating services.
- Benthic macrofauna play a vital role. Species activities are responsible for modifying the rate of material processing, and consequently affect many ecological principles.
- Ecosystem resilience is influenced by key species maintaining feedback interactions between biological and either chemical or physical processes. To maintain the adaptive capacity of coastal ecosystems, these important functional linkages and the diversity of species need to be maintained or enhanced to facilitate functional replacement in response to environmental change.
- Cultural services largely rely on the integrity of the entire system. All principles can be linked to cultural service provision in some capacity e.g., the experience of leisure and recreation has links to productivity (e.g., act of fishing) and water clarity (swimming, aesthetic value), which are in turn influenced by material processing and habitat provision.

The report also considers the impact of anthropogenic stressors on ecological service delivery. Despite mechanistic differences in their actions, many similarities were found in the effects of different stressors. The broad range of effects of stressors indicated that all ecosystem goods and services could be affected. The general ecological principles approach emphasised the importance of shallow, well-mixed coastal waters in underpinning provisioning and regulating services. There was an important distinction between service provision and utilisation; the areas where services are utilized may not be the same as the areas where they are generated. The principles approach was a useful tool for understanding the linkages between ecological functioning and the goods and service provided. Recommendations could be made for the management of coastal resources and the preservation of coastal services based on the principles:

- The high number of ecosystem functions and principles linked to ecosystem goods and services suggest that management actions which improve the ecological system may have multiple and wide ranging benefits for human welfare, thus cost is offset by multiple gains. Conversely, deterioration in coastal ecosystems can cause declines in a broad range of services with potentially high and significant costs.

- The potential spatial distinction between service ‘provision’ and ‘utilisation’, highlights the risks of society not sufficiently appreciating the value of estuaries or shallow coastal ecosystems.
- If shallow systems are allowed to degrade, there is an increased risk that there will be a degrading of service provision and consequently service utilisation in the other areas.
- There is a need for management strategies that are effective at conserving both the source and the output of services and a need to further understand the environmental system.
- There is a need for improved economic valuation of all services to support management decisions.

2 Introduction

The acknowledgement that nature has great value is implicit to New Zealanders. As a society, New Zealand has been founded on the direct exploitation of ecological systems that support our farming, forestry, fishing and tourism. More recently, tourism has grown and New Zealand and many of the products exported from our country have been heavily marketed on our clean and green image (e.g., *100% Pure New Zealand*, www.newzealand.com). Tourism is now our largest industry contributing over $21.7 billion (NZD) to the economy annually (www.stats.govt.nz). Tourism and our clean green image are not simply about the direct exploitation of nature, but rely on many non-fiscal benefits including aesthetic, cultural and spiritual values. Auckland is a major hub for tourism and in particular its harbours, estuaries, beaches and coastline showcase much of how New Zealand values its natural environments (all locations in Auckland city are approximately <4 km from the shoreline). Auckland has an array of coastal ecosystems that provide many benefits to Auckland residents and tourists alike. Coastal ecosystems produce not only goods, such as fish and shellfish, and amenity and recreational values but in addition ecosystem functioning provides important services that play crucial roles in supporting human, plant and animal populations. However, beyond a limited subset of 'direct' or obvious benefits, the breadth and detail of services delivered by ecological systems is much less well known.

A current issue is that ecosystem 'goods and services' are currently either not recognised or are excluded from decision-making processes as a result of the failure of markets to reflect true costs. Most ecosystem services are provided free and usually taken for granted. It is only when these services are lost that actual monetary costs are incurred. Failure to understand and value the benefits that coastal ecosystems provide increases the risk that changes will be made that disadvantage society. Decision-making by national or regional government where fiscal issues are a key driver, are often based on marginal value or marginal cost. Failure to incorporate latent components and recognise the 'total' value can lead to decisions being made where the final costs outweigh the benefits (Constanza et al. 1997, Hanley et al. 2001). Thus, it is imperative that decision makers are provided with the knowledge and tools that allow them to firstly understand, and then to value, the benefits provided by ecological systems sufficiently. Ecological systems are faced with increased human pressures including toxic pollution, eutrophication, sedimentation, habitat fragmentation, invasion of non-native species, over harvesting and climate change (Roberts and Hawkins 1999, Levin et al. 2001). These environmental pressures often result in changes in ecosystem service provision, thus understanding the impacts are vital for service management. This is recognised as a key objective of the Auckland Regional Growth Strategy: safeguarding the environment by enabling the use of the region's air, soil, land and water resources in a sustainable manner.

The aim of this report is to increase the understanding of goods and services provided by estuarine and coastal systems, by answering the following questions:

1. What is the full range of ecosystem goods and services relied on by humans?
2. Which ecosystem goods and services are provided in the Auckland coastal environment?
3. How do ecosystem functions underpin these goods and services and affect their regulation and delivery?
4. What is the spatial and temporal delivery of ecosystem goods and services?
5. What is the spatial and temporal appreciation of ecosystem goods and services?
6. What are the implications for future delivery of ecosystem goods and services in light of various anthropogenic impacts?

Question 1-2 are addressed in section 3, which provides definitions and examples of key terminology and establishes a comprehensive a framework for ecosystem service evaluation. Question 3 is addressed in sections 4 and 5, which explores how ecosystem services delivery is maintained through ecosystem functioning. To avoid the overwhelming difficulty and complexity of incorporating all ecological information and recognising that many details are still unknown, a 'general principles' approach has been developed in answering this question. This links together ecosystem functioning and services in a way that is both meaningful and useful but not overwhelmed by detail that in many cases would be difficult to support, owing to limited ecological knowledge. Questions 4 and 5 relate to temporal and spatial utilisation and provision of ecosystem services and are the focus of section 6. This section looks at the connectivity between places and times that can lead to mismatches between where services originate from and where they are specifically valued. This section also addresses the relative importance of different divisions of the coastal environment for service provision. Finally, question 6 addresses the issues of human perturbation on the marine environment and implications for the delivery of ecosystem goods and services in the future and is in section 7.

3 Ecosystem functions, goods and services

Research addressing ecosystem services has received increased attention in last few decades (Pearce 1990, DeGroot 1992, 1994, Daily 1997, Daily et al. 2000). A wide range of studies has defined and grouped ecosystem processes, functions, goods and services and environmental and economic frameworks in multiple ways; often depending on the research discipline of the author and to suit different contexts from local to global scales (Constanza et al. 1997, Pimentel et al. 1997, DeGroot 2002). Therefore, a definition of what we mean by ecosystem 'functions' and ecosystem 'goods and services' is a necessary starting point.

'Ecosystem' is used to describe a 'dynamic complex of plant, animal and micro-organism communities and their non-living environment that interact as a functional unit' (Figure1) (Convention on Biological Diversity, 2010). Ecosystem processes are thus the physical, chemical and biological actions, which link organisms and their environment. Ecosystem functions are often considered to be the summation of multiple processes which drive the transfer of energy and matter. However, in practice the terms ecosystem process and function are used synonymously in the literature and include nutrient cycling (Lohrer et al. 2004, Hewitt et al. 2006, Thrush et al. 2006), production (Tilman et al. 1996, Thrush et al. 2006, Lohrer et al. 2010), community respiration (Lohrer et al. 2010) and decomposition (Wardle et al. 1997, Levin et al. 2001) (Figure 1).

Ecosystem goods and services are used to describe the outcomes resulting from ecosystem functions that have implicit value to humankind. Thus, they can be seen as a way to link 'natural' systems and process to human well-being (Figure 2). Ecosystem goods and services are defined as "the direct and indirect benefits that mankind receives or values from natural or semi-natural habitats" (Daily 1997, Constanza et al. 1997, Boyd and Banzhaf 2007). Ecosystem 'goods' are the tangible resources that can be extracted and utilised by humans, such as food and raw materials. Ecosystem services are the abilities of ecological systems to provide favourable conditions for humans by processing material or providing intrinsic benefits (e.g., water filtration, dampening environmental pressures, recreational opportunities).

Figure 1:

Ecosystem structure and functioning – the simplified pathways of material and energy flows that occur within habitats.

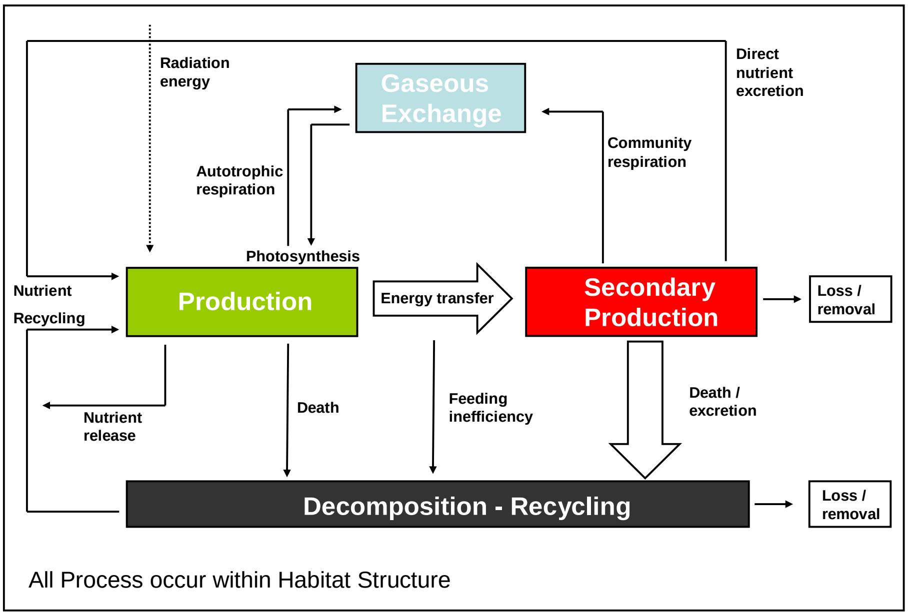
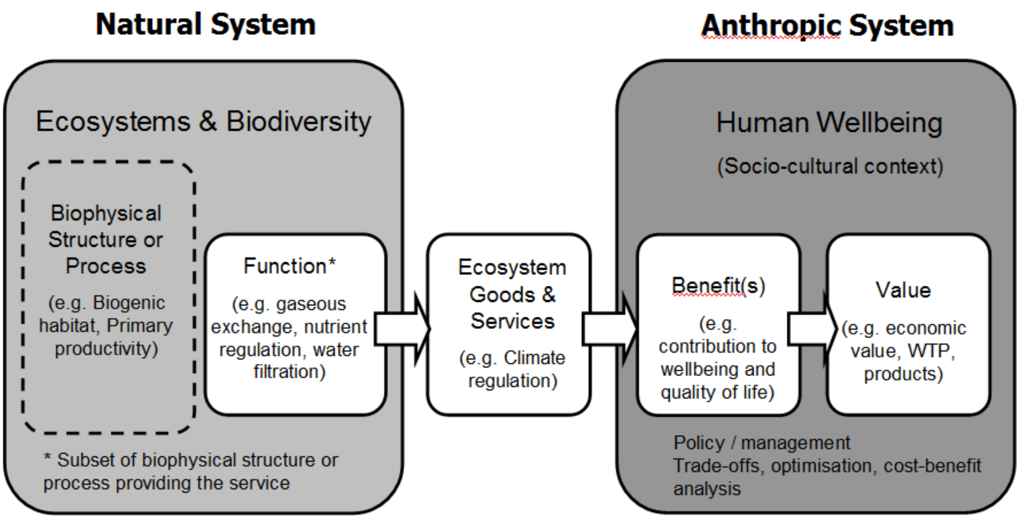


Figure 2:
The ecosystem goods and services framework which links ecosystem processes and attributes to human well-being (adapted from Haines-Young and Potschin 2010).



An overarching classification and useful synopsis was delivered by the Millennium Ecosystem Assessment (MA), a 5 year international collaboration that assessed the state of ecosystem services, the drivers of ecosystem change and the implications for human wellbeing (Millennium Ecosystem Assessment 2005, Norgaard 2009). The MA used four major categories which are illustrated in Figure 3. 'Provisioning' services are those whereby natural resources are exploited for food or other material resources (goods). 'Regulating' services are those in which humans benefit from the regulation of essential ecosystem functions such as nutrient cycles (de Groot 2002). 'Supporting' services are those processes that underpin all other ecosystem services and thus provide indirect benefits. 'Cultural' services are the non-material benefits that human's value from the environment (Beaumont et al. 2007). These four overarching categories can be divided into 17 separate goods and services (Table 1) (Constanza et al. 1997, de Groot 2002, Beaumont et al. 2007, Coasts and Oceans OBI). Table 1 excludes 3 services listed by Constanza et al. (1997): soil formation, water supply and pollination. While these services may influence the delivery of others they are not considered to be directly or predominantly produced in the coastal marine environment and fall outside of the scope of the current report. The following sections (3.3.1 to 3.3.4) provide definition and explanation of the goods and services listed in Table 1 and also give examples of marine species or resources involved with the service delivery in Auckland and New Zealand.

Figure 3:
The interactions between ecosystem services and human wellbeing, adapted from the Millennium Assessment's frame work for ecosystem goods and services. Note that processes operate on a variety of spatial (local, regional, global) and temporal (short-term, long-term) scales.

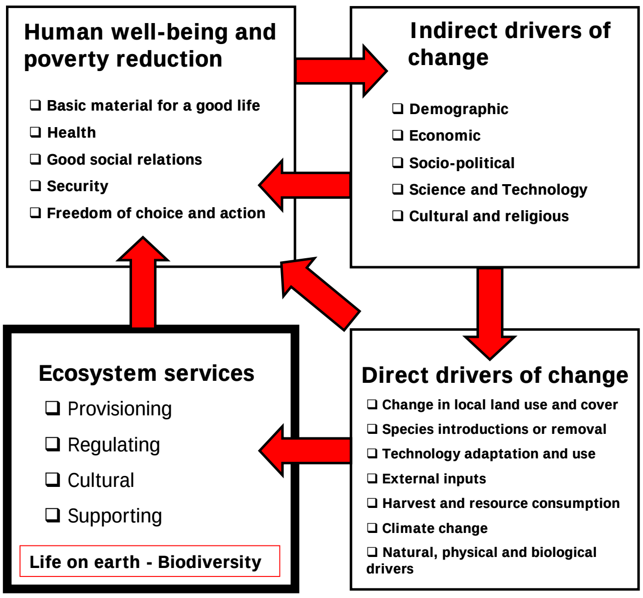


Table 1:

Ecosystem goods and services that are obtained from coastal marine environments.

Over-arching Categories	Ecosystem Goods and Services
Provisioning services	Food provision
	Raw materials
	Genetic and medicinal resources
Regulating services	Disturbance prevention
	Waste treatment, processing and storage
	Water regulation
	Sediment retention
	Biological control
	*Gas and climate regulation
	*Nutrient regulation
Supporting services	Resilience and resistance
	Habitat structure
Cultural services	Cultural and spiritual heritage
	Leisure and recreation
	Cognitive benefits
	Non-use benefits
	Speculative benefits

* Nutrient regulation and gas and climate can also be classified as supporting services.

3.1 Provisioning Services

Food provision:

This is defined as the extraction of organisms for human consumption. In New Zealand, coastal food provision is a fundamental and highly valued service. The annual value of seafood ranges from $1.2 to $1.5 billion across New Zealand's EEZ; with approximately 600,000 tonnes collected per annum (http://www.fish.govt.nz). Many different species of fish are targeted; however, Snapper (*Pagrus auratus*) is the most iconic fish species for the North Island. It is a highly import fishery, with recreational landings comprising a significant proportion of the total catch (34.4%, Mfish 2008). In 2008 the export value of snapper from the Auckland East region (SNA1) was $22.63 million. Other important species include Tarakihi (*Nemadactylus macropterus*) and King fish (*Seriola lalandi*) which are of high recreational and customary value.

Recreational fisheries were 24% and 68.2% of the total catch, with 2008 export values of $130,000 and $83,000 NZD for these species respectively from the Auckland East region (TAR1 and KIN1). In the local coastal environment other important species for food provision include intertidal bivalves such as cockles (*Austrovenus stutchburyi*), pipis (*Paphies australis*) and oysters (*Crassostrea gigas*) and gastropods (*Amphibola crenulata*). Cockles are a highly valuable food resource particularly for local consumption by recreational and customary harvesting (89%, Hauraki Gulf and Bay of Plenty COC1C region), although export stock is relatively low (<7%). Subtidally, mussels, scallops, kina, paua, paddle crabs and crayfish are commercially and culturally prized.

Raw materials:

This provisioning service is defined as use or extraction of renewable materials for all purposes except that of human consumption. Excluded from this definition is the extraction of hydrocarbons, minerals and sand mining for construction as these are not considered to be renewable over a timescale relevant to humans. In a global context the extraction of renewable materials includes water and salt, which are removed through desalination, fishmeal for aquaculture and farming, seaweed for fertilizer and other industrial processes (Beaumont et al. 2007) In the Auckland Region the extraction of shell hash for aquaria trade and landscaping is probably the main use. Also under this definition is the generation of renewable energy from tidal and wave electric power generation which are likely to be increasingly important for New Zealand.

Genetic and medicinal resources:

Organisms may contain genetic information and biogenic-chemicals that have uses in the medical and pharmaceuticals industries (Sipkema et al. 2004). Examples in New Zealand include developments in anti-cancer research using species of sponge e.g., *Mycale hentscheli* from Marlborough Sound (Page et al. 2005) or *Lissodendoryx* sp. (Munro et al. 1999). The future discovery and use of marine resources is covered in the speculative value below (section 3.4)

3.2 Regulating services

Disturbance prevention:

This refers to the mitigation of environmental disturbance by biogenic structures or biogenically modified habitats. Species can create biological structures that modify flow and reduce coastal erosion and protect coastal housing and property. In the 2004 Asian Tsunami, the presence of mangroves and other vegetation was found to substantially reduce the severity of damage in certain areas (Danielsen et al. 2005). This is supported by modelling which has shown mangroves, under certain conditions, reduce the maximum flow pressure of such events by 90% (Hiraishi et al. 2003). The specific role of mangroves in the event of an Auckland tsunami would be influenced by many factors, but it is likely that in some locations this vegetation would play a role in dissipating wave energy. Marine species that dissipate energy (i.e., waves, tidal surges, storm surges) are those that form and affect surface topography such as mangroves, seagrass (Fonseca and Calalan 1992), saltmarshes (Brampton 1992, Morris et al. 2004), and mussel and oyster reefs. Intertidal and beach sediments also dissipate wave energy and this function is in part influenced by resident species that stabilise sediments (macrofauna and microphytobenthos) and modify the form and increase the spatial extent of these habitats.

Waste treatment, processing and storage:

This refers to the removal of waste material, organic (e.g., sewage) or inorganic (e.g., heavy metals), through a combination of recycling, burial and storage (Beaumont et al. 2007). In coastal systems, the modification and removal of waste material is an extremely complex process (e.g., see Gadd et al. 2010). Organisms affect the burial, resuspension, transportation, dilution, transformation into more or less toxic states and the biomagnification of toxic substances up into the food chain (e.g., Townsend et al. 2008, Beaumont et al. 2008). Organic material such as sewage may be used as an energy source in macro- and microbial processes and this overlaps with the nutrient recycling service (Oviatt et al. 1986, 1993). Many of the species dwelling in coastal and estuarine soft-sediments around the Auckland region play important roles in the cycling of sediments and consequently organic and inorganic contaminants (Figure 4). For example the mud crab *Austrohelice crassa,* a dominant species in upper estuarine areas, can turnover between 7 and 84% of the top 4 cm of sediment each month depending on sediment type (Needham et al. 2010). The common cockle *Austrovenus stutchburyi,* when in sufficient density will accelerate sediment deposition and contaminant accumulation in the sediment through its ability to filter material from the water column (Gadd et al. 2010). Species such as *Macomona liliana* can affect sediment movement by significantly decreasing the sediment stability (Lelieveld et al. 2004).

Water regulation:

This refers to the role of the land and vegetation in regulating runoff into rivers and estuaries and the subsequent fluvial discharge, although this may be considered a primarily a terrestrial service. Contributions in New Zealand may stem from vegetation on the fringe of estuaries and the coast: salt marshes i.e., sea rush (*Juncus kraussii*), jointed rush (*Apodasmia similis*) and ribbonwood shrub (*Plagianthus divaricatus*), that then moving inland make way to salt meadow species i.e., Saltwort (*Sarcocornia quinqueflora*), remuremu (*Selliera radicans*) and shore primrose (*Samolus repens*) and finally beyond this coastal scrub. In the Auckland region the capacity for the land and flora to regulate water discharge may be limited due to the high percentage of land which has been modified and concreted with the discharge of material regulated through stormwater management practises. Impervious areas accounted for 42% of land within the Auckland Metropolitan Urban Limits in 2008 (ARC 2009). However, there are substantive vegetated areas of mangroves in the upper estuaries that perform this function.

Sediment retention and generation:

This refers to the role of vegetation and sediment biota in the process of sediment retention. Plant species such as mangroves and seagrass, when in sufficient densities, prevent the erosion of intertidal sediments and increase the levels of deposition (Figure 4). Polychaetes that form tube-mats can be important in stabilising sediments (Thrush et al. 1996). Also species can play a role in sediment generation, for example, bivalve shells at Pakiri Beach - at this location there are approximately 25 km of beach and sandy sediments that run offshore for about 4 km to a depth of about 40 m. In this area, like many around New Zealand, carbonate derived from mollusc shells makes up 40-70% of the sediment by weight (Hilton, 1990).

Biological control:

This is the control and regulation of food web dynamics by the actions of key species. Key predators are able to control the abundances of prey and lower trophic levels through their trophic-dynamic relationships with species. This biological pressure may also reduce the invasion success of non-native species. Examples of key predators include many species of birds and fishes (Thrush et al. 1994, Cummings et al. 1997, Shears and Babcock 2002, Doak 2003). Predatory invertebrates include crabs (*Ovalipes catharus*), worms (nereids and glycerids) and molluscs (*Comminella* spp., *Octopoda* spp.). Other species are able to exert control through non-predatory actions, such as *Macomona liliana* (Thrush et al. 1996) and *Echinocardium cordatum* (Lohrer et al. 2008) which influence community composition through bioturbation activity and *Austrovenus stutchburyi* (Pawson 2004) which affects algal populations in enclosed estuaries though filtering activity.

Gas and climate regulation:

This describes the balance of chemical exchange between the oceans and atmosphere that is influenced by the activities of marine organisms. For example, many species are involved with the exchange and regulation of carbon fluxes and play a role in climate regulation. Carbon dioxide is absorbed by the oceans with exchange driven by the utilisation of dissolved forms into the metabolism and skeletal structure of species. In coastal systems, molluscs are key removers of carbonates from the water into skeletal structures. This 'biogenic' bicarbonate is important as it represents long-term storage of carbon; for example, even moderately low mass shells can exist for 100-1000 years. Further offshore, carbon dioxide is removed by oceanic plankton species such as diatoms (Boyd et al. 2004) and coccolithophores (Iglesias-Rodríguez et al. 2002). All marine primary producers take up carbon dioxide for photosynthesis and a large amount of carbon is held in this standing stock. Other key exchanges between the atmosphere and the oceans include the supply and removal of volatile organic halides, ozone, oxygen and dimethyl sulphide (Beaumont et al. 2007). Human impacts can affect gaseous exchange, as eutrophication has a significant impact on both nitrous oxide and methane emissions mediated through anaerobic sediments (Bange et al. 1998).

Nutrient regulation:

This refers to the recycling of organic and inorganic nutrients by the activities of marine species. Recycled nutrients can supply a significant proportion of the nutrient demand for primary production (Sundbäck et al. 2003). The form and rate of nutrient supply to the phytoplankton may also be one factor influencing the risk of harmful algal blooms. Consumption and decomposition pathways recycle organic material and interact with microbial processes, regulating the fluxes of nitrogenous, phosphorus and sulphurous material. Nutrient recycling is undertaken in both pelagic and benthic habitats, but in estuarine and coastal habitats seafloor organisms are very important and it has been estimated that 1/3 – 1/2 of the primary production on the continental shelf is fuelled by processes occurring in the seafloor sediments.

3.3 Supporting services

Resilience and resistance:

Coastal ecosystems and their communities may be able to absorb natural and human pressures. When disturbed, the speed at which they can recover and return to the pre-disturbed state is important for service delivery. Thus, ecosystem resilience and resistance are vital supporting services underpinning the maintenance of all other services. Resilience and resistance are influenced by the role of key species that maintain feedback interactions between biological and either chemical or physical processes.

Habitat structure:

Marine habitats provide living space for species and so are a prerequisite for the provision of all other goods and services. Many species play a principal role in habitat provision through their modification or creation of habitat space (Figure 4). For example, many species provide complexity and structures that are used as nursery areas and predator refugia by other species. Coral reefs are the most iconic example, but many other organisms modify the topography of the seafloor in New Zealand including oyster, *Atrina* and mussel reefs, abundant bivalves which create shell hash, root structure from mangroves, seagrass meadows and tubeworm mats (de Juan and Hewitt 2011). Less obvious, but also vitally important are the habitat modifiers that work below the sediment surface e.g., burrowing crabs (Needham et al. 2010), thalassinidean shrimp (Berkenbush et al. 2000, Atkinson and Taylor 2005) and bioturbating worms (Kristensen 2001), and urchins (Lohrer et al. 2004, 2008).

3.4 Cultural services

In addition to the essential life services listed above, coastal ecosystems contribute to human wellbeing and provide a number of social or amenity services. These contribute to the quality of life and are known to have economic value; indicated from techniques such as discrete choice modeling (Batstone and Sinner 2010), willingness to pay (WTP) or willingness to accept (WTA); Hanley et al. 2001). The economic valuation of these services is beyond the scope of current report, which instead focuses on ecosystem processes which generate them. However below we list examples of the various cultural services.

Cultural and spiritual heritage:

This refers to the benefits provided by marine resources that are of significance to the cultural and/or spiritual identities of the community. The value of marine resources has a strong presence in Maori spirituality. Human communities living by the sea have attached importance to marine ecosystems that are integral to the cultural definition of the community. The collection of food from marine resources (fishing and gathering) in addition to provision services is of strong cultural importance to many New Zealanders inclusive of Maori.

Leisure and recreation:

This refers to the use of, or engagement with, marine resources for stimulation or relaxation of the human body and mind. This is one of the more obvious services that the coastal system provides with many examples in the Auckland region and strong links to the tourism industry. Sailing and boating are a key activity in the Auckland area with 1 in 3 families owning a yacht or launch and the region containing just under half of New Zealand's registered sailors (Ihaka 2010). Other leisure pursuits include nature watching, diving and fishing. Inshore and shallow water pursuits include numerous beach activities such as swimming, sunbathing and beach-walking; with the latter popular all year round (Figure 5).

Cognitive benefits:

This refers to the value of natural marine resources to cognitive development, which includes education and scientific research. Many marine species provide stimulation for cognitive development, and much of the marine research effort in New Zealand occurs within the Auckland Region. Information contained within natural systems can be adapted or exploited by humans for societal development (Beaumont et al. 2007). Global examples of this include the use of polychaete spines in photonic engineering with potential benefits to communication technology industries (Parker et al. 2001).

Non-use benefits:

This refers to the values that humans place in aspects of ecological systems or of certain species, despite the fact that they are unlikely to directly interact with them. Non-use values cover existence and bequest. 'Existence value' is the contentment derived in the knowledge that an ecosystem contains a natural resource or species i.e., dolphins, seabirds, landscapes and/or geological features, even if it is never personally experienced. This can be motivated by selfish reasons or by altruism. 'Bequest' value is the importance placed on the availability of a natural resource or the survival of a species for future human generations.

Speculative benefits:

These are also known as 'option use values' and describe the importance that humans place in coastal ecosystems having attributes that may become valuable in the future, for example future medical research (Hanley et al. 2001). Option use value is likened to an insurance premium in which potential or actual users of the coastal environment are willing to pay to secure resource availability, although the size and sign of option uses are uncertain (Ready 1995).

Figure 4:

Tamaki Estuary by Otahuhu, Auckland. Examples of ecosystem goods and service provision.

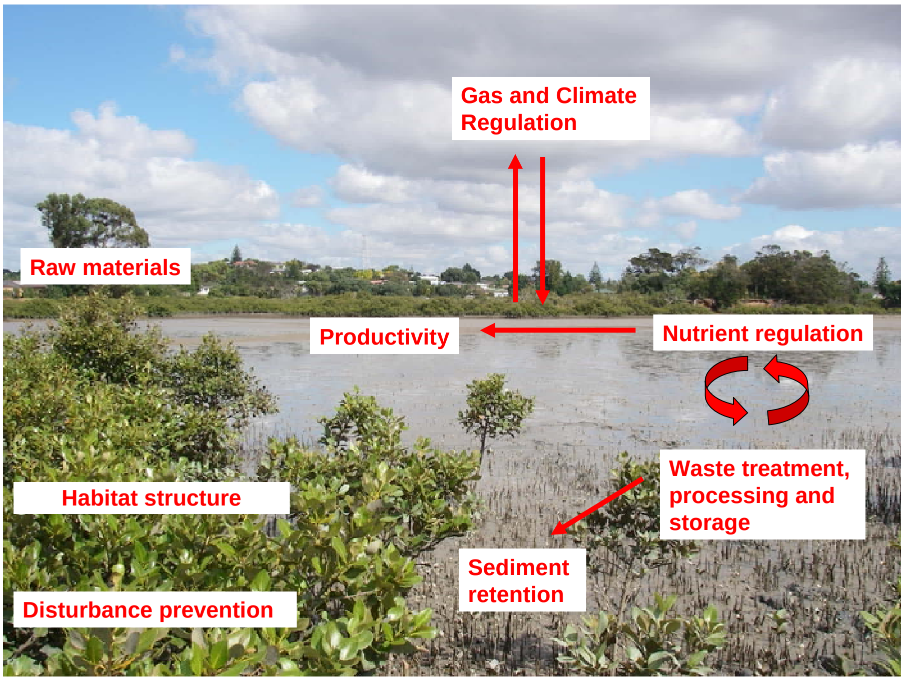
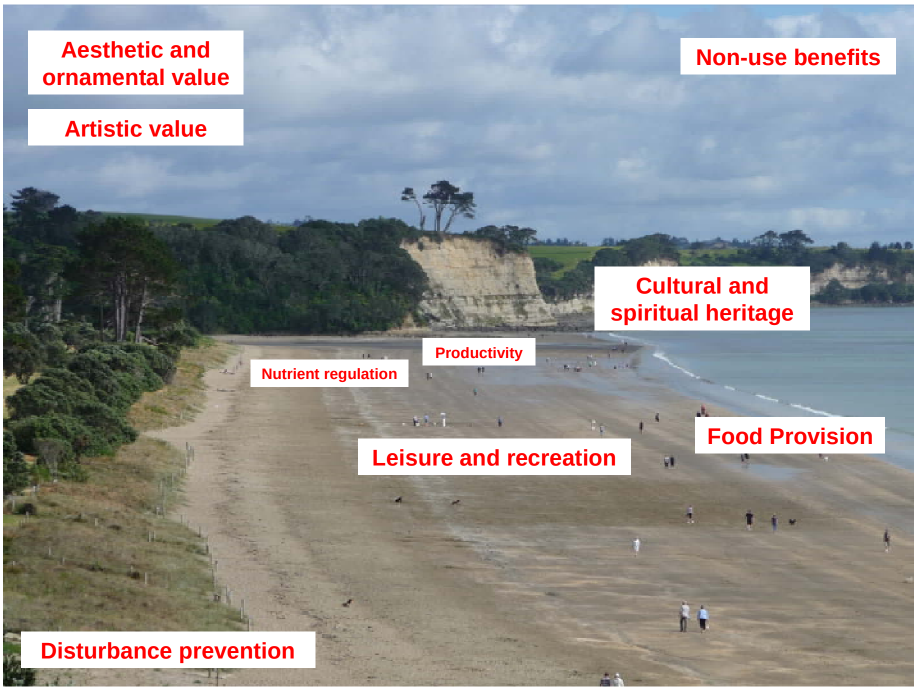


Figure 5:

Long Bay, Auckland. Examples of ecosystem goods and service provision.



4 Ecosystem service provision and the underlying ecosystem processes

Having defined the range of ecosystem goods and services for the Auckland coastal region (section 3), sections 4 and 5 explore how the delivery of these services is underpinned by ecosystem functions and relates to different ecosystem properties. By understanding in greater detail the processes which generate ecosystems goods and services, we can begin to evaluate their spatial and temporal dynamics and understand how human impacts may modify their delivery.

The summary statements from an Auckland Regional Council workshop (February-March 2008, with national experts in stormwater contaminants and their effects) addressing stormwater stressors and ecosystem service provisions are relevant for linking ecosystem service provision to the underlying ecosystem functioning. The workshops emphasized that system and process complexity, in combination with a lack of full scientific certainty, meant that predicting the exact nature and pathway of stressor impacts was not possible. This work revealed that the specific extent of stressor effects was dependent on the specific nature of particular processes and interactions (e.g., the rate of nutrient recycling in the sediment will be affected by sediment grain size, hydrodynamic conditions and the resident benthic community, all of which interact). Nevertheless, some confidence could be placed in broadly describing the eventual stressor effects (e.g., loss of shellfish beds, loss of large long-lived organisms, biodiversity decrease) necessary for determining environmental futures for Auckland's coasts and estuaries.

Relevant summary statements (March 2008):

- In many cases contaminant inputs are diffuse and episodic, complicating management and the interpretation of cause and effect relationships. Moreover, different stressors interact, sometimes amplifying adverse effects, and the effects of stressors can vary along environmental gradients.
- The potential for interaction between stressors increases as we move from the detection of immediate stressor effects to broader consequences on ecosystem function and changes in ecosystem services.
- There are many knowledge gaps and uncertainties, nevertheless management actions that ensure the resilience of these ecosystems are imperative.

Comprehensively linking goods and services to the ecosystem functions that underpin them is a major challenge that would involve the integration of all system processes: feedback loops, synergies and antagonisms. A full detailing of goods and services and ecosystem functions is thus unhelpful and decreases the clarity needed to link these two together. Instead, a simplification of the ecological system can be more useful. General ecological principles (taken from peer-reviewed literature) have therefore been used to define linkages between goods and services, and ecosystem functions (Tables 2 and 3, section 5). The selected principles cover a broad and comprehensive range of ecosystem functions. The principles have focused on the ecology of coastal areas including estuaries; however this technique could also be applied to other systems and landscapes.

4.1 Ecological Principles Approach

The following sections summarise the key general ecological principals that are relevant to service provision in coastal area and provides examples from peer-reviewed literature. In total, 19 ecological principles have been generated from ten main principal themes.

4.1.1 Productivity

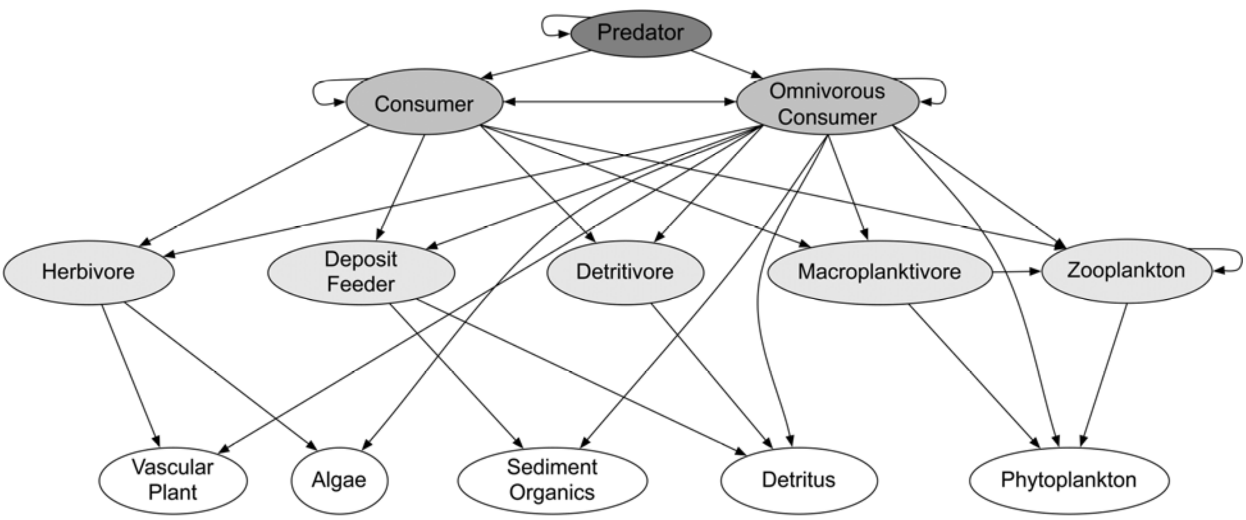
- Principle 1: Benthic productivity is an important contributor to system productivity and is greater in shallow than deeper waters.
- Principle 2: Benthic productivity is greater in sandy substrates (i.e., sediment dominated by particles in 2 – 0.063mm size range) compared with finer, muddy substrates (<0.063mm).
- Principle 3: Healthy areas that maintain productivity at low trophic levels should fuel productivity at high trophic levels.

Primary production is the process by which photoautotrophs (plants, algae, certain microbes) synthesize organic compounds from inorganic constituents using energy from solar radiation (Tait and Dipper 1998). In intertidal and shallow coastal waters, microalgal benthic primary production is an important contributor to the overall system productivity (Cahoon 1999). Shallow intertidal flats are among the most productive habitats on the planet, with primary productivity as high as 4,000 g C m^{-2} yr^{-1} for estuaries and shallow reefs (Leith 1978). Annual productivity of benthic microalgae is estimated to contribute 500 million tonnes of carbon globally (Cahoon 1999). Coastal areas disproportionately contribute to the overall marine system productivity. For example, continental shelves represent 7.2% of the marine surface area but contribute 16.9% of the annual primary production, estuaries and reefs are 0.55% of the area, but contribute 7.3% and benthic macroalgal beds (0.028%) contribute 1.8% (Ryther 1962; Leith 1978). Intertidal flats can constitute a substantial proportion of the total area (Hume et al. 2007) and are typically characterized by higher nutrient fluxes and warmer temperatures than deeper water equivalents. In addition, shallower waters are often well-lit, supporting primary production, although there is a strong interaction with turbidity. Temporal and spatial variations in temperature, irradiance, turbidity, tidal exposure, salinity, nutrient supply, sediment type and bioturbation influence the biomass and species composition of microphytobenthos (Admiraal and Peletier 1980, Blanchard et al. 1997, Underwood and Kromkamp 1999). The standing stock of microphytobenthos is not always a good indicator of system productivity. Sandwell et al. (2009) found a high standing stock of microphytes at a muddier site relative to a neighbouring sandier site. However, productivity is not a stock variable, it is a rate variable (quantity of oxygen or carbon or biomass produced per area per time), and sandy sites often have higher rates of primary production.

High primary productivity is not indicative of a healthy system as excessive nutrient loading (eutrophication) can cause large blooms of algae and/or plankton that result in significant ecological disruptions (Smith et al. 1999). Problems associated with eutrophication include toxic algal blooms, hypoxia and anoxia, community shifts and poor transfer of energy to higher trophic levels (Rosenberg 1985, Paerl and Whitall 1999). While eutrophication is a problem in North America and Europe it is still relatively minor in New Zealand.

Secondary production refers to all heterotrophic organisms that feed on primary producers (e.g., grazers and other primary consumers), other heterotrophic species (consumers, predators) or associated organic material (e.g., scavengers and decomposers, Figure 6). The transfer of energy through food webs is dependent on many species-specific factors including population sizes, feeding efficiencies, the spatial and temporal stability of the species populations, the number of trophic levels and number of species connections (Paine 1980).

Figure 6:
Generalised coastal/estuarine food web structure (from Byrne et al. 2007) Arrows point from predators to prey.



4.1.2 Material Processing

- Principle 4: Mudflats are predominantly involved with the storage and sequestration of organic and inorganic material. Sandflats are predominantly involved with the processing, modification and recycling of organic and inorganic material.
- Principle 5: Shallow waters where the water column is well-mixed, have higher rates of processing relative to deeper, less well-mixed areas which can be storage 'sinks' for material.
- Principle 6: Species can play a dominant role in determining the magnitude and direction of nutrient exchange.

Nutrient regulation is mediated by the activities of macrofauna that inhabit soft sediments. Bioturbation has a profound impact on the chemical environment of the sediment (Rhoads and Stanley 1967) elevating the level of cycling (Svensson et al. 2000). Bioturbation and ventilation activity increase the penetration of oxygen into the sediment (Aller and Aller 1998, Volkenborn et al. 2010) which promotes oxic processes. Increases in the surface area of the sediment-water interface and oxic-anoxic boundary from biogenic structures (Kristensen 1984) also promotes greater exchange between the two chemical environments and increases the amount of chemical exchange per unit area (Nielsen et al. 2004, Hansen et al. 1996). Many species have been demonstrated to affect nutrient regulation including bivalves (Sandwell et al. 2009, Thrush 1996, Hewitt et al. 2006), crabs (Needham et al. 2010) worms (Thrush et al. 2006) and urchins (Lohrer et al. 2004, 2005).

Estuaries are characterised by strong environmental gradients where the inputs of material from terrestrial, freshwater and marine habitats are processed and transformed (Levin et al. 2001). Intrinsic differences between sandy and muddy sediments modify the interaction between species and sediment, affecting the capacities for storage and processing. Sandflats are dynamic systems. High rates of organic material turnover in sand are facilitated by the prevailing physical conditions (highly permeable, well oxygenated, rapidly turned over sediment, Eagle 1973) and high microbial activity (Hansen and Kristensen 1997, De Beer et al. 2005). This is despite the fact that coarser sediments often have lower counts of microbial cells through lower specific surface area of larger particles (Keil et al. 1994). High turnover of organic material means that sandflats have significant roles in the recycling of nutrients (Lohrer et al. 2010a, b). Contaminants such as heavy metals are usually associated with fine particles and so sandy areas have lower concentrations because the hydrodynamics prevent the long-term settlement and accumulation of contaminants bound to fine sediments (Cortesao and Vale 1995; Mitchener and Torfs 1996). Mudflats are less dynamically active environments relative to sandy habitats, and tend to act as depositional areas. As a result, mudflats typically have higher metal concentrations, as they bind to smaller particles (Hatji et al. 2002), and are organically rich. Smaller sediment particle sizes mean that mudflats have lower porosity and permeability, which reduces the availability of oxygen and the transport of porewater through the sediment.

The underlying differences between mud and sand with respect to material processing also hold true for differences in water depth. Shallow, well-mixed waters have relatively higher rates of turnover due the maintenance of exchange gradients through increased flushing and transfer of material, higher light and temperature levels (stimulating the microphytobenthos) and nutrient regeneration. Deeper water tends to be darker, colder and less mixed resulting in reduced processing and increased storage.

4.1.3 Sediment Stability and Turnover

- Principle 7: Flora and fauna that filter food or nutrients from the water column and maintain a sedimentary lifestyle have a stabilising effect on the sediment.
- Principle 8: Organisms that have a mobile life-style, moving through and on the sediment surface, or those that deposit feed have a destabilising effect on the sediment.

The activities of benthic species can have either stabilising or destabilising effects on the sediment environment, although the nature of these effects is related to the size, density, activity and types of species. Plants typically have stabilizing effects, such as mangroves and seagrass, with root structures that influence hydrodynamics (Jones et al. 1997), reducing the flow conditions near to the bed and dissipating current and wave energy (Gambi et al. 1990). These actions also increase the rate of sediment deposition and accumulation (Gacia et al. 1999, Heiss et al. 2000, Granata et al. 2001, Bos et al. (2007). The microphytobenthos can produce extracellular polysaccharide biofilms (Holland et al. 1974) that bind and stabilize the surface sediment particles, increasing the erosion threshold. Similar effects are seen for fauna that construct structures that emerge from the sediment surface. For example, high densities of *Atrina* can lead to skimming flow and a decrease in the amount of resuspension, with the size and density of patches affecting sediment stability (Coco et al. 2006). Also, spionid polychaetes that create dense tube mats can stabilise the sediment surface (Thrush et al. 1996). Filter-feeding organisms with reduced mobility tend to stabilise the sediment. Unlike deposit feeders, suspensions feeders do not need to constantly explore and rework the sediment. However, the attribute of suspension feeding does not guarantee stabilizing effects. Cockles are common suspension feeders, but at low and intermediate density they disrupt the surface sediment by extensive horizontal movement (Whitlatch et al. 1997, Cummings 2007). At high densities they cease to move and form stable patches that can armour the seabed and reduce erosion.

4.1.4 Gaseous Exchange

- Principle 9: Shallow-well mixed waters have a higher ratio of gaseous exchange than deeper, less well-mixed waters.
- Principle 10: Shallow-well mixed waters have higher concentrations of bacteria relative to deeper, less well-mixed waters.

Marine sediments play an important role in the cycling of gaseous material. Marine sediments affect the fluxes of oxygen and carbon dioxide. Marine sediments are involved in the cycling of methane with aerobic and anaerobic oxidation of methane releasing carbon dioxide or sulphide into the pore water. The principles of material processing have been outlined in section 4.1.2 and 4.1.3 above, and in reference to gaseous exchange these principles continue to apply. Shallow waters have a greater flux of material, with supply and removal gradients more readily maintained, relative to deeper waters.

4.1.5 Structure Formation

- Principle 11: Organisms produce and mediate habitat structures that are utilised for predation refugia, nurseries for juvenile life stages, or as surface area for attachment of other species.
- Principle 12: Mollusc species and other organisms with carbonate shells or skeletons sequester carbon and contribute to carbonate-based sediments.

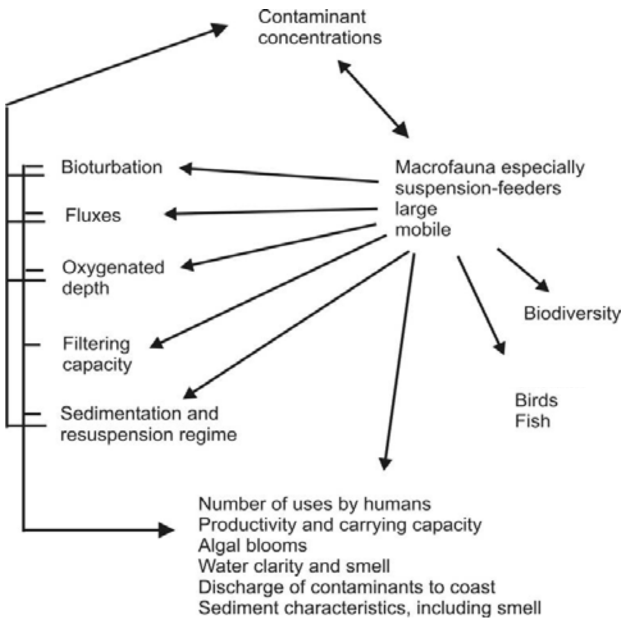
Multiple species in coastal and estuarine systems are responsible for the formation and modification of habitat structure. This is most commonly through modification of materials that change the chemical or physical environment (see sections 4.1.2 and 4.1.3 above). However, other organisms can directly create and form habitat structure structures themselves. Habitat formers that increase the topographic complexity of the seafloor provide places for smaller organisms, including juvenile fish, to hide from roaming predators. They also provide additional settlement surfaces for other organisms to live, increasing the architectural complexity and providing food resources (Skilleter 1994, Thrush and Dayton 2002). In addition to providing this structural capacity, molluscs also remove calcium carbonate from the water column during shell formation. In these taxa, shell material is made by the mantle, which secretes ammonia and creates alkaline conditions suitable for deposition of calcium carbonate. This shell formation sequesters carbon, removing CO_2 from the water column and can form a significant part of the sediment matrix.

4.1.6 Turbidity

- Principle 13: Suspension-feeders can influence the suspended sediment concentration and clarity of overlying water through their filtration activity.
- Principle 14: Increased suspended sediment concentrations reduce primary production through increased light attenuation.

Suspended sediment is a primary determinant of light penetration/ attenuation in the water column and the magnitude of the affect is determined by the size and concentration of sediment particles. The inputs of suspended sediments into estuarine and coastal water bodies are modified by the activity of benthic suspension feeders. These organisms filter out material from the water column during feeding activity (Figure 7); with sediment either ingested or rejected as mucous-packaged pseudofaeces (Ellis et al. 2002, Hewitt and Pilditch 2004). The importance of these activities has been highlighted in the Auckland Regional Council's three year 'Suspension Feeding – Contamination Programme' (Townsend et al. 2008, 2009, Gadd et al. 2010) which has examined the multiple impacts of cockles. The general principle is that, when present in sufficient densities, cockles accelerate the rate of sediment deposition. The degree and significance of this is dependent on initial suspended sediment concentration, water volume, residence time or flushing rate of a particular body of water and suspension feeder density.

Figure 7:
An indication of system complexity with multiple impacts, interactions and feedback processes of benthic species (from Townsend et al. 2008).



4.1.7 Connectivity

- Principle 15: Connectivity is required to translocate material between different locations within an estuary, harbour or coastal area and from shallow to deeper waters.
- Principle 16: The levels of connectivity influence the supply and removal rates of biotic and abiotic material.

Connectivity refers to the level of interaction or connectedness between locations. This can occur through both physical processes (i.e., the flushing and physical exchange of water with dissolved/suspended material between locations) and through biological pathways (i.e., the transfer of energy through the food web translocating material/energy from one location to another). The level of connectivity facilitates material being transported to different locations where it can either be utilised or stored. The level of connectivity interacts with the level of material processing (Principles 4-6) and determines the balance of material exchange. Systems that are heterotrophic do not directly produce enough energy to satisfy their energy requirements and become reliant on allochthonous inputs (Polis and Hurd 1996). Under these conditions the levels of connectivity are of paramount importance. Connectivity is also important for resilience, as disturbed patches are reliant on the levels of connectivity to supply juveniles and colonists allowing the community to recover (Thrush et al. 2008).

4.1.8 Biodiversity

- Principle 17: Space and resource occupancy by native species can decrease invasion risk.
- Principle 18: Higher biodiversity increases the number of functional groups and/or the range of species within a functional group.

The importance of biodiversity as a factor in the maintenance of high levels of ecosystem processing and other ecosystem attributes is still a contested issue. There is some evidence that biodiversity reduces the chance of invasion by non-indigenous species (NIS) at the local scale (Kennedy et al. 2002). Theory suggests that high diversity results in more efficient use of available space and resources and this limits the opportunity for invasion success (Elton 1958, Stachowicz et al. 1999). This has been shown in theoretical and small-scale experimental studies (McGrady-Steed et al. 1997, Tilman et al. 1997, Tilman 1999) although wider implications are unknown. However, Stachowicz and Byrnes (2006) suggest that the 'biotic resistance' of high diversity is only applicable when resources are limited and that this does not always occur in nature.

High biodiversity increases the functional diversity of a community when a greater number of species causes a wide range in species traits to be present. Equally, high biodiversity supports functional redundancy if there are multiple representative species within a functional group. These aspects of higher diversity may be beneficial for disturbance recovery when there is redundancy of species with stabilising roles (Insurance Effect - Yachi and Loreau 1999, Portfolio Effect – Doak et al. 1998, Tilman et al. 1998) or if there is a greater chance of containing species that respond differentially to perturbations (Naeem and Li 1997). Despite the importance of understanding these fundamental diversity issues for resource management, much of the biodiversity – resistance/resilience understanding has been based on theoretical or simple small-scale experiments with limited empirical evidence. Furthermore, we know that the activities in marine communities that underpin the delivery of ecosystem services are often dominated by the actions of a limited number of 'key' or 'critical' species. Although direct evidence in support of the role of species richness in resistance/resilience is lacking, there is some evidence that maintaining the ecosystems adaptive capacity is important and from a management viewpoint a precautionary approach is needed. It may be sensible to presume that higher biodiversity can have ecological benefits i.e., for resilience, until the body of evidence proves otherwise, as the cost of losing biodiversity may be substantially greater than the cost of protecting it unnecessarily. For the purpose of the general principles construct (Principles 17 and 18), a precautionary approach is adopted and it is assumed that biodiversity has a positive impact on both invasion and disturbance resistance.

4.1.9 Complexity

- Principle 19: Ecosystems are fundamentally complex and the system details are important.

Although simplification can be made for the construction of the general principles, it is necessary to remember that the complexity and details of ecological systems are fundamentally important. Principles 1 – 18 all emphasise that many ecosystem processes are temporally, spatially, extrinsic factor, stochastically, community composition and dose specific. This caveat should be considered when applying the results of the principle construct to specific situations or case studies.

4.2 Stressors

A key aspect of understanding the relationship between ecosystem functioning and the delivery of goods and services is to understand the impacts that anthropogenic impacts have in this process. It is therefore necessary to include some general principles on key human disturbances.

- Overharvesting

Overharvesting in our context is the action of extracting marine species at an exploitation rate that restricts the functionality of the species. Overharvesting of shellfish, such as cockles, removes and reduces the productivity (Principle 3) and decreases the transfer of energy through the marine food web (connectivity, principle 16). Reduction in shellfish numbers decreases shell formation (Principle 12) and impacts on sediment processing (turbidity Principle 13, processing Principles 6 and 8). Overharvesting of fish species may reduce the number of predators in the marine environment (biological control, table 1) and affect the flow of energy through food webs (connectivity, Principle 16). Overall, if overharvesting is severe it may result in a functional shift and a decline in biodiversity (Principles 17 and 18).

- Pollutants

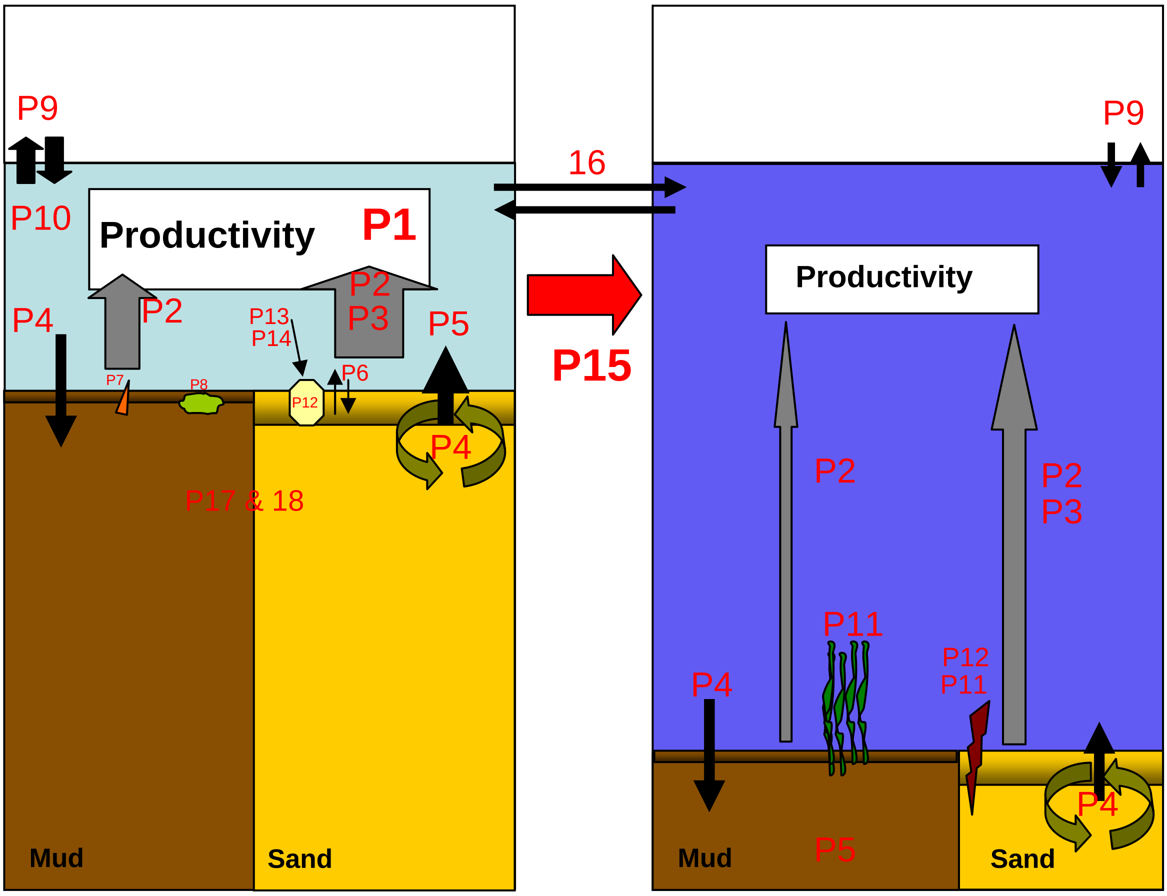
Pollution incorporates many of the contaminants that are associated with human activity and stormwater runoff in the coastal environment, including sediment, heavy metals, polychlorinated biphenyls and hydrocarbons. The chronic impacts of these pollutants are dose- and situation-dependent and difficult to predict with high levels of certainty. However, the Auckland Regional Council workshops series (February-March 2008) addressing stormwater stressors and ecosystem service found that, while the precise severity and chronology of toxic effects were complex, general statements could be made. For example, pollution reduces system productivity (Principle 3) and results in the loss of larger species, which affects the trophic structure (connectivity, Principle 16). This form of pollution has a negative impact on biodiversity and system resilience (Principle 18).

- Direct physical disturbance

Direct physical disturbances are human activities that result in disruption to the integrity of the marine environment. For example, the disturbance of benthic communities from fishing gear (separate from overharvesting) (Dayton et al. 1995, Jennings et al. 2001, Thrush and Dayton 2002), channel dredging, mining, sediment deposition, mangrove removal and building engineering structures, all of which, if the disturbance effect is large enough or frequent enough, can change the functional characteristics of soft sediment communities (affecting Principles 4 to 8). This can affect trophic dynamics (Principle 15), reduce the availability of habitat structure (principle 11) and cause decline in biodiversity (principle 18). Elevated deposition of sediments into the coastal marine environment changes sediment composition by increasing the percentage of fines (Principles 1 – 3), increasing turbidity (Principle 14), reducing productivity and causing a loss of habitat structure (principle 11), carbon storage (Principle 12) and diversity (Principle 18). The resultant changes to community structure affect sediment processing and exchange (Principles 4 - 8). The impact of certain human wastes in the marine environment i.e., plastic litter, tyres, glass etc. may have little ecological effect beyond an extremely localised impact. However, there may be a direct effect on the societal services, with a perceived reduction in the aesthetics of the environment (section 3.3.4).

Figure 8:

Schematic flow model linking the general principles and showing the flow of energy from shallow well-mixed water (left) through to deeper offshore water (right). Arrow thickness and box size are an indication of process magnitude for comparability between shallow and deep regions.



5 Linking ecosystem functions to the delivery of goods and services

5.1 Applying the Principles

The general principles approach (section 4) has covered a wide range of ecosystem functioning and ecological attributes that are important for the coastal environment in the Auckland Region. These principles (Table 2) have covered biological interactions with the physical and chemical parameters and the processing of material between different energy states and locations. Furthermore, these principles have served to differentiate functioning between shallow and deeper water. Figure 8 demonstrates schematically the information contained within the principles. It highlights that processes occur more quickly in shallow waters and are consequently of greater magnitude (Principles 1, 5 & 9). Each principle can be aligned to the relevant ecosystem goods and services. In this respect, the ecological principles can be used as a more effective proxy for ecosystem functioning in the generation of ecosystem goods and services. Using the principles may be a more appropriate approach as they can be spatially and temporally defined, not limited with respect to number and based on the varying levels of information available. This facilitates a greater understanding of the relationship between ecosystem properties and goods and services (Figure 9). This is shown in Table 3, where each of the 17 ecosystem goods and services has been evaluated for relations with the 19 ecological principles. Each principle was not limited to the number of ecosystem goods and services to which it could be assigned, nor was there a minimum number to which they had to be applied.

Following the assignment of general principles to ecosystem goods and services, Table 3 could be assessed for:

- The frequency of occurrence of each principle across the services to identify key ecosystem functions (commonly involved vs. rarely involved).
- The range of principles involved for each individual ecosystem good or service to assess multi-functional vs. discrete functional underpinning.
- The identification of specific principles with the differing over-arching categories of ecosystem goods and services.

Table 2:

Summary of the Ecosystem Principles.

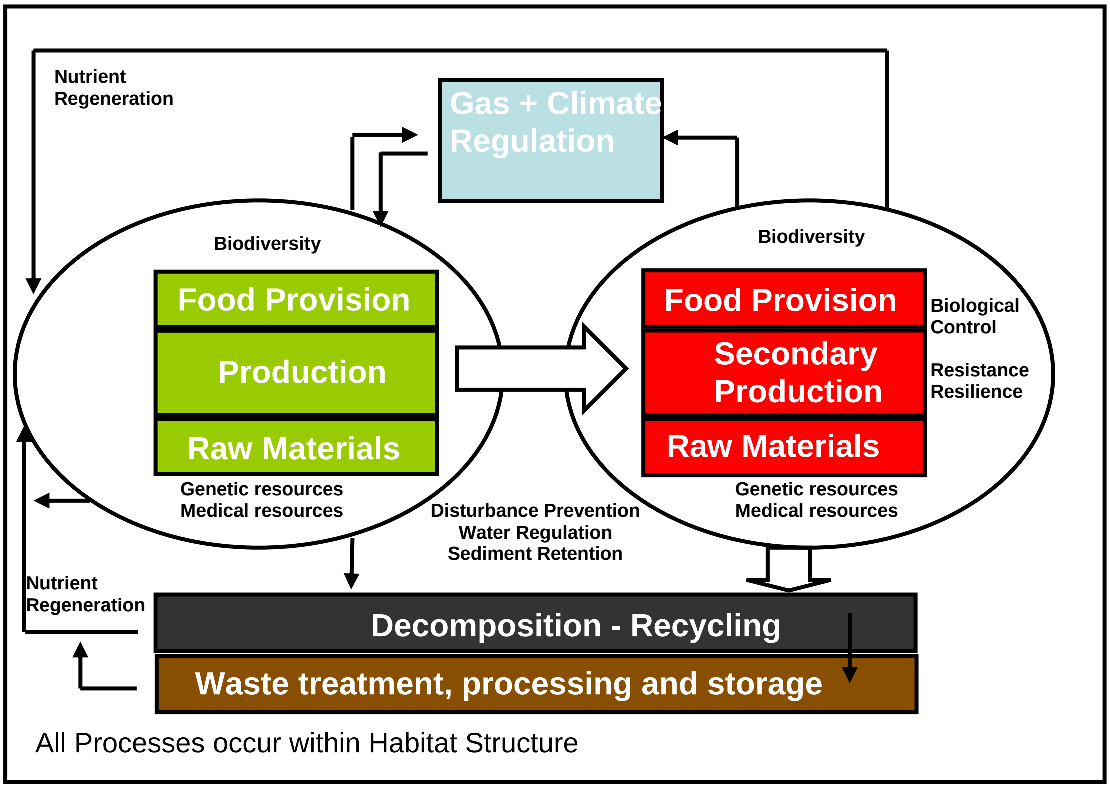
Principle	Definition
1	Benthic productivity is an important contributor to system productivity and is greater in shallow than deeper waters.
2	Benthic productivity is greater in sandy substrates (i.e., sediment dominated by particles in 2 – 0.063mm size range) compared with finer, muddy substrates (<0.063mm).
3	Healthy areas that maintain productivity at low trophic levels should fuel high productivity at trophic levels.
4	Mudflats are predominantly involved with the storage and sequestration of organic and inorganic material. Sandflats are predominantly involved with the processing, modification and recycling of organic and inorganic material.
5	Shallow waters where the water column is well-mixed, have higher rates of processing relative to deeper, less well-mixed areas which can be storage 'sinks' for material.
6	Species can play a dominant role in determining the magnitude and direction of nutrient exchange.
7	Flora and fauna that filter food or nutrients from the water column and maintain a sedimentary lifestyle have a stabilising effect on the sediment.
8	Organisms that have a mobile life-style, moving through and on the sediment surface, or those that deposit feed have a destabilising effect on the sediment.
9	Shallow-well mixed waters have a higher ratio of gaseous exchange than deeper, less well-mixed waters.
10	Shallow-well mixed waters have higher concentrations of bacteria relative to deeper, less well-mixed waters.
11	Organisms produce and mediate habitat structures that are utilised for predation Refugia, nurseries for juvenile life stages or as surface area for attachment of other species.
12	Mollusc species and other organisms with carbonate shells or skeletons sequester carbon and contribute to carbonate-based sediments
13	Suspension-feeders can influence the suspended sediment concentration and clarity of overlying water through their filtration activity.
14	Increased suspended sediment concentrations reduce primary production through increased light attenuation.
15	Connectivity is required to translocate material between different locations within an estuary, harbour or coastal area and from shallow to deeper waters.
16	The levels of connectivity influence the supply and removal rates of biotic and abiotic material.
17	Space and resource occupancy by native species can decrease invasion risk.
18	Higher biodiversity increases the number of functional groups and/or the range of species within a functional group
19	Ecosystems are fundamentally complex and the system details are important.

Table 3:

Linking ecosystem function and structure through to ecosystem goods and services. In the associated ecological principle column each row applies to the specific ecosystem good or service.

Over-arching Categories	Ecosystem Goods and Services	Associated Ecological Principles
Provisioning services	Food provision	P1, P2, P3, P11, P14, P15, P16, P19
	Raw materials	P1, P2, P3, P11, P14, P15, P16, P19
	Genetic and medicinal resources	P1, P11, P17, P18, P19
Regulating services	Disturbance prevention	P1, P7, P8, P11, P19
	Waste treatment, processing and storage	P1, P4, P5, P6, P7, 15, 16, P19
	Water regulation	P1, P13, P19
	Sediment retention	P1, P5, P7, P8, P19
	Biological control	P1, P17, P18, P19
	Gas and climate regulation	P1, P4, P5, P6, P9, P10, P12, 15, 16, P19
	Nutrient regulation	P1, P3, P4, P5, P6, P12, 15, 16, P19
Supporting services	Resilience and resistance	P1, P15, P16, P17, P18, P19
	Habitat structure	P1, P7, P8, P11, P12, P19
Cultural services	Cultural and spiritual heritage	P1 - 19
	Leisure and recreation	P1 - 19
	Cognitive benefits	P1 - 19
	Non-use benefits	P1 - 19
	Speculative benefits	P18, P19

Figure 9:
Ecosystem good and services applied to the ecosystem function approach.



5.2 Consequences of the ecological principles for the delivery of goods and services

5.2.1 Provisioning services

Provisioning services are strongly and logically linked to ecological principles involving ecosystem productivity (Table 3). Productivity not only (directly) supplies food and raw materials, but is the source of much of the material and energy that flows through the ecosystem. Consequently, connectivity is also a reoccurring principle for provisioning services, as it links disparate locations together and facilitates the movement of material and energy within and among locations (Table 2). The ability of ecosystems to provide material that is of value as genetic or medicinal resources is linked to the biodiversity principles. This is through a greater number of species increasing the probability that a one will be of specific use.

5.2.2 Regulating services

The overarching category of the regulating services is highly multi-functional and is related to a large number of principles (Table 3). This reflects the diverse range of services that are incorporated under this theme. Productivity is still an important feature as a provision of the 'building blocks' which can be recycled, translocated and modified. Productivity is also linked to the organisms that facilitate many of the cycles and regulating processes: Table 3 shows that marine coastal species (secondary productivity) play a key role in the regulating services (Principles 6, 7, 8, 11, 12 & 13). Table 3 also iterates that shallow water habitats are important resources in the cycling of material and that processes occur faster in these habitats than their deeper water equivalents (Figure 8).

5.2.3 Supporting services

Similar to the regulating services, the principles indicate that species play a key role in underpinning the supporting services (Table 3). Organisms modify the physical and chemical environment and provide substrates that benefit many forms of life. Species also play a role in alleviating and preventing the effects of disturbance. Through this biotically mediated role, productivity becomes an essential principle for the maintenance of secondary productivity and the biomass of the important species (Table 3). Supporting services are also sustained by the diversity principles because different species have different attributes and thus, collectively, a diverse system can better cope with a range of different disturbances. As both gas and climate regulation and nutrient regulation can also be considered supporting services (in addition to regulating services), the overarching supporting theme is multi-functional in its underpinning (14 of 19 principles involved).

5.2.4 Cultural services

Cultural services largely rely on the integrity of the entire system (Table 3). The broad and multi-faceted nature of cultural services makes it difficult to exclude any of the principles. For example, the experience of leisure and recreation has links to productivity (e.g., fishing) and water clarity (swimming, aesthetic value), which are in turn influenced by material processing and habitat provision which are facilitated through species actions. Diversity may be of particular importance for cognitive benefits and non-use benefits. The general indication was that social values were reliant on the system integrity and a holistic approach rather than any specific subdivision of functioning or ecosystem structure.

5.2.5 General Consequences

Across the range of all ecosystem services there were consistent patterns relating to the principles and ecosystem functioning. Productivity is a key component of all service supply. Productivity not only (directly) supplies food and raw materials, it is the source of material and energy that flows through ecosystems and is thus connected to all regulating and supporting services. However, the activities responsible for modifying the rate of many processes and providing habitat structure are species-specific. This re-emphasises the established importance of species in ecosystem functioning (e.g., Emmerson et al. 2001, Webb and Eyre 2004, Needham et al. 2010). The diversity of species can also play an important service role and is likely a key ecological attribute in the recovery of natural systems to disturbance. The high frequency of numerous ecological principles relating to the delivery of specific goods and services indicates that multi-functionality is commonplace in ecosystem service provision (Table 3). Thus, the maintenance of ecosystem goods and service is reliant more on the integrity of the whole ecosystem than specific and discrete elements. This multi-functionality with respect to service provision has implications for ecosystem management. It suggests that improvements to the ecological system may have multiple and wide ranging benefits for human welfare, off-setting the costs of these improvements. Conversely, deterioration in ecological health/functioning through increased human pressures can cause a broad range of service decline with potentially high and significant costs. Finally, the complexity and detail of the ecosystem functions underpinning goods and services is of fundamental importance (Table 3, Principle 19). Therefore, research that continues to explore and understand ecological relationships must continue.

6 Spatial variation in ecosystem goods and services: provision and utilisation

The general ecological principles approach clearly reveals the importance of shallow, well-mixed coastal waters in underpinning provision and regulating services (Table 3, Figure 8). In addition, a comparison of Figure 4 and 5 demonstrates that services are not distributed uniformly and that different areas or habitats are responsible for delivering different services. This section looks at the connectivity between places and times that can lead to mismatches between where services originate from and where they are specifically valued or utilised.

Provisioning services

The general ecological principles indicate that productivity is highest in areas of well mixed, shallow water, with intertidal flats supporting high productivity (section 4.1.1 and Figure 10a). When shellfish, such as cockles and pipis, dominate the value of food provision the source of productivity and the site of values are the same. However, applying this to the Waitemata Harbour, which is more limited with respect to harvestable shellfish beds, a different pattern may emerge. A greater importance and value may be placed on line fishing and this would result in entirely different areas being valued for food provision (Figure 10b). The life histories of different fish species are complex, but the general assumption is that the productivity in offshore areas benefits from connectivity to the productivity of inshore areas (Principle 15). The principles also highlight that high productivity at low trophic levels is required to maintain high productivity at higher trophic levels (Principle 3). In this instance, there is a disparity between areas of service utilisation and areas important for service provision. At the same time, it becomes obvious that services can be location dependent and determined by the species involved.

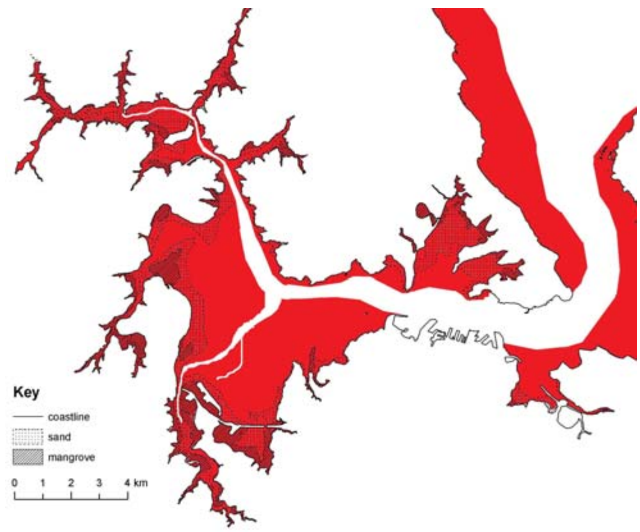
Regulating and supporting services

The provision of regulating and supporting services occurs at different scales and locations, depending on the process of interest. Differences in gaseous exchange between shallow and deeper waters do occur (Principle 9), and consequently there is spatial variation in delivery. However, gas and climate regulation fundamentally operate at larger scales than that of an estuary, harbour or coastal location. Nutrient regulation is another process that can also be observed at a large scale, although local variation can be important (e.g., Sundbäck et al. 2003). Intertidal and subtidal sediments can be graded for their levels of nutrient exchange based on sediment type, depth, community composition etc. A similar system can be used to determine roles in the retention of sediments in the coastal environment. While regulating and supporting ecosystem services may be produced at varying scales, their utilisation is not always spatially explicit. Instead, the majority of regulating and supporting services are consumed passively and ubiquitously. Although awareness is increasing, many people are still not conscious of the role ecosystems play in supporting life (Daily et al. 1997, Salzman 2005). Processes such as gas regulation, producing the oxygen we breathe, or material processing and nutrient regeneration are often taken for granted.

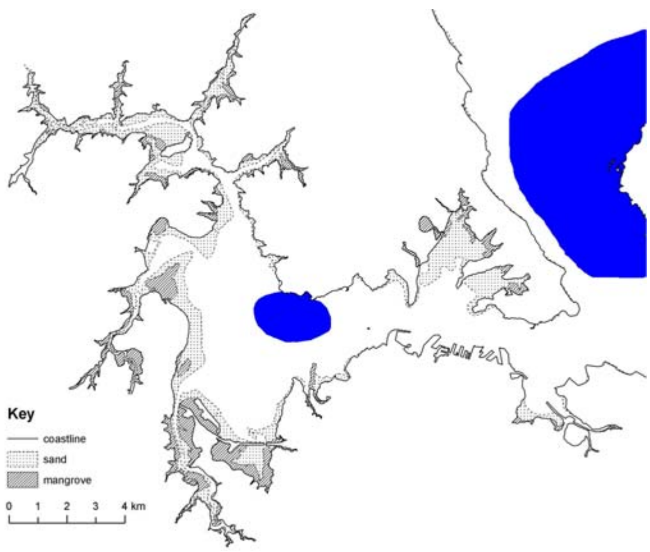
Figure 10:

An idealised schematic to emphasise the difference between areas of service creation and service uptake; a.) Represents areas that, at a coarse level, have higher productivity based on shallow waters and trophic connectivity (Principles 1 and 3) indicated in red. Incorporating productivity differences relating to grain-size (Principle 2), was beyond the scope of this schematic; b.) The areas of greatest use for recreation fishing indicated in blue, where vessel density exceeds 100 per km^2. Schematic based on NEBIS data from aerial surveys (Ministry of Fisheries).

a)



b)



Cultural services

People value different parts of the environment for many reasons, but a comparison of Figures 4 and 5 indicates that specific attributes may be rated more highly for cultural services than others. For example, coastline and offshore areas can offer greater opportunity for recreation and leisure pursuits than upper estuarine areas and may be more highly valued as a result. Areas like Mission Bay, St Heliers Bay and Long Bay (Figure 5) may be perceived to have better scenery and greater aesthetic value compared to inner harbour locations and thus valued for activities such as swimming, dog walking and sun bathing. Similarly, offshore locations may be of greater value than the inner harbour sites for recreational activities like fishing (Figure 10). Choice Modelling by Batstone and Sinner (2010) found Auckland residents had a strong preference for outer coastal locations relative to the middle and upper harbour sections. They also found residents to place importance on specific attributes of water quality, the quality of underfoot conditions and ecological health. Each of these qualities is dependent on processes and activities that occur in other locations; in particular on the regulating services provided by inner harbour and estuarine locations. Further work is necessary to determine the spatial preference for specific recreational and cultural activities and the attributes of greatest value.

7 Stressor impacts on ecosystem goods and services

Historically, the value of ecosystems for providing services has been ignored until disruption or loss highlights their retrospective importance (Daily et al. 1997). As many services do not have a market value, they are often undervalued and signals of changes in their supply or deterioration often pass unnoticed by most of society. Human impacts in the Auckland region are placing increasing pressure on the environment with stormwater contaminants (Green 2008), invasive species (Hayward et al. 1997, Cranfield et al. 1998) and increasing sediment accumulation occurring. Daily et al. (1997) noted that when disruption has occurred it can be difficult or impossible to reverse the effects on a time scale relevant to society. For example, high rates of terrigenous sediment have accumulated in the Mahurangi Harbour following recent land-use practices and developments (Cummings et al. 1994). Despite positive action (e.g., see Mahurangi Action Plan 2010-2030), the extended residence time of sediment pollution means that its presence and effects will be seen for decades into the future.

The principle approach can be used to link the impacts of anthropogenic stressors through to their effects on ecosystem services delivery. Table 4 expands the details discussed in Section 4.3 and shows where stressors can modify the ecosystem functioning which underpins the delivery of goods and services. This is done by assessing whether there is a negative impact on the processes within the general ecological principles. Linking this to Table 3, which indicates which principles are involved with the different goods and services, can help establish the effects of stressors on service delivery. The important point here is that we are focused on ecosystem responses to stress or disturbance rather than defining the specific stressors. Despite their mechanistic differences, Table 4 indicates that there are many similarities between the different anthropogenic stressors at a general level with respect to their principal ecosystem effects. For example, although overharvesting and toxic pollutants are very different by nature, they both have negative impacts on productivity, by impacting populations and damaging/removing predators, larger bodied organisms and shellfish beds. This reduces the productivity and the flow of energy within the system. With many of the principles based on the presence, diversity and activities of organisms, there can be multiple and broad effects for both of these stressors.

The broad effects of anthropogenic stressors on the ecological principles (Table 4), coupled with the high number of principles relating to ecosystem goods and service delivery (Table 3), indicates a clear pathway for effect. This means that every principle that is affected by stress is linked to an ecosystem good or service and that all goods or services can be affected. A compounding factor is that the resilience and resistance capacity is affected by all stressors, which may reduce the system's ability to recover from the broad effects of stress. It is important to highlight that the principle analysis should not be interpreted as indicating that all stressors are equal. Stressors differ greatly in their effect threshold, their residence time and their spatial extent. For example, the recovery dynamics of a beach that has been over-harvested compared to one that has lost its bivalve population due to contamination would be expected to be quite different. What the principle analysis demonstrates is that at a broad level, stressors can operate in a similar way ecologically.

Principles which are not directly impacted by all anthropogenic stressors include the relative differences between sand and muddy sediment (Principle 4) and also between shallow and deeper water (Principle 5, 9 & 10); although the former may be influenced by the stressor through variation in species activity. Direct anthropogenic disturbances such as increased sedimentation may impact turbidity and light attenuation (Principle 14) but this may also have cascading effects.

The ecological principles approach has allowed a qualitative assessment of the stressor effects; however, there is insufficient information at the current time to support a quantitative assessment.

Table 4:
Links between stressors and the general ecological principles. x marks indicate when a stressor is negatively linked to a principle.

General Principles (see Table 2)	Overharvesting	Toxic pollutants	Direct anthropogenic disturbances
1	x	x	x
2	x	x	x
3	x	x	x
4			x
5			
6	x	x	x
7	x	x	x
8	x	x	x
9			
10			
11	x	x	x
12	x	x	x
13	x	x	x
14			x
15	x	x	x
16	x	x	x
17	x	x	x
18	x	x	x

8 Conclusions

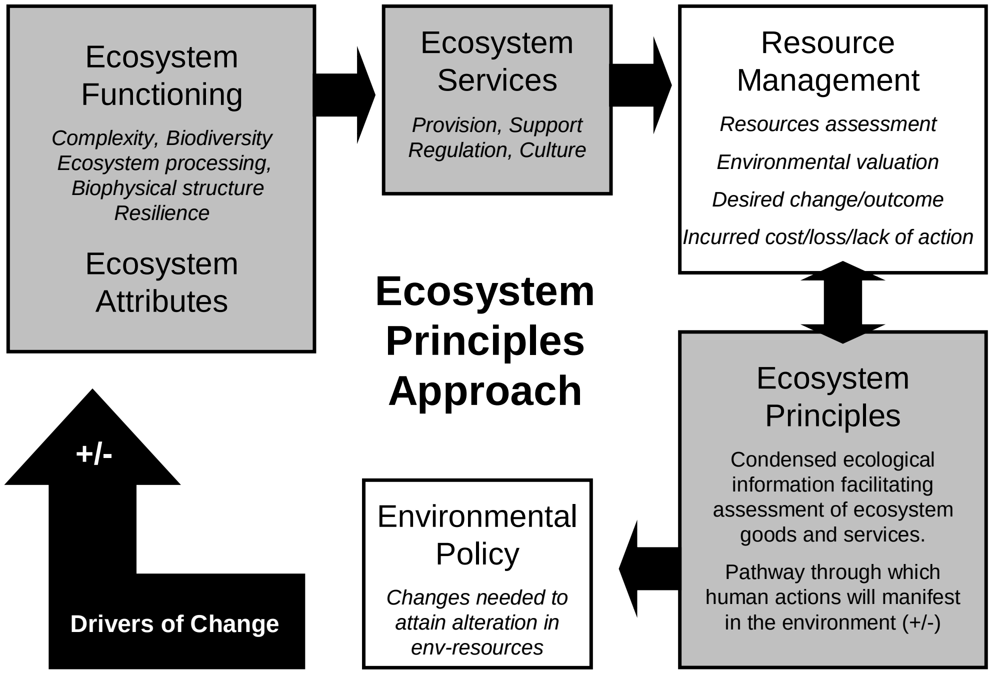
8.1 The Ecological Principles Approach

The ecological principles approach appears a useful tool for furthering the understanding and linkages between ecosystem functioning and the delivery of goods and services. It has allowed general statements to be made which are useful at a broad level and are still supported by peer-reviewed literature. The approach can provide a first step for suggesting whether there will be changes in service delivery that result from potential management actions (Figure 11). Thus, the principles could be used to highlight potential future scenarios where service provision will increase, decrease, or remain the same, depending on the level of action or inaction. The ecological principles could also be adapted and incorporated for approaches which map and spatially define ecosystem services. Mapping approaches are typically data driven, but in the absence of empirical data, the principles may be used to define likely service distribution (i.e., relating to sediment, bathymetry, known habitats etc.,). There are examples of the use of surrogate information as a proxy for services (e.g., Yapp et al. 2010) and methods like the ecological principles approach could be adapted to use the best available knowledge and the general understanding of a system.

The key findings of this approach are that many aspects of ecosystem health and integrity are important for maintaining ecosystem goods and services. The patterns that have emerged are:

- Productivity is a key ecosystem function. Productivity supports biodiversity, determines the biomass of organisms responsible for many other functions and the transfer of material and energy through the ecosystem. As all organisms exhibit growth, productivity can be considered to underlie all ecosystem goods and services in the coastal zone.
- In New Zealand coastal zones estuaries, tidal flats and shallow waters are the most productive areas and consequently support many services; although they are not often intrinsically valued by society and can be areas of high human impact.
- The study re-emphasizes the key role that species play in ecological systems, and links them directly to the provision of ecological services which humans are reliant upon.

Figure 11:
The 'Ecological Principles Approach' framework: Ecological principles are used as a simplification of an ecosystem (grey boxes). The ecological principles can be used in resource management to assist in the decision making process, that feeds into policy (white boxes). Changes in ecosystem functioning/services will be detected during environmental/social monitoring by resource managers, who can decide if further action is to be taken.



8.2 Anthropogenic stressors

The study has defined how specific stressors are likely to interact with general ecological principles (Table 4). Through this we can connect to the effects on ecological services. We found that:

- Most of the common and prevalent stressors in Auckland coastal environment broadly have similar effects on the ecological principles.
- The general effect of stressors is to degrade ecological systems by reducing the survivorship and population sizes of species that provide many aspects of service delivery. Species are responsible for biomass and energy transfer and many ecosystem processes.
- Impacts on biodiversity may reduce the capacity of ecosystems to absorb natural and human disturbances and to recover from them; although direct evidence to support this is limited. Biodiversity does have proven value for cognitive and non-use benefits. As a precautionary approach, it is recommended management strategies take a cautionary approach and conserve biodiversity.

- Impacts are highly complex (Thrush et al. 2008) and highly dependent on spatial and temporal location. Thus, progress beyond the qualitative and general effects in sections 4.3 and 7 is not possible at this time under this framework.
- The storage capacity (Principle 4) of marine sediments means that stressors can have long residence times in the coastal environment. Consequently, efforts to improve the condition of the marine environment may take considerable time and effort.

8.3 Implication of the study for management practices

The ecological principles approach can be used to suggest areas that managers need to consider and areas where knowledge is needed to improve management:

- The high number of ecosystem functions and principles linked to ecosystem goods and services suggest that management actions that improve the ecological system may have multiple and wide ranging benefits for human welfare, offsetting the cost of improvements. Conversely, deterioration in coastal ecosystems can cause a decline in a broad range of services with potentially high and significant costs.
- There is an important distinction between service provision and utilisation such that the areas where the service is utilized may not fully encompass the area needed to provide the service (Figure 10). Aucklanders' show a greater willingness to pay for improvements in quality at outer coastal beaches compared to middle and upper harbour locations (Batstone and Sinner 2010). However, because many of the outer coastal beach services are generated or underpinned elsewhere, within harbour sites need to be improved to achieve these benefits.
- The simplicity of the ecological principles approach means that it may be used as an effective education tool. For example, to simplify and explain why action and funding are required in areas, even if they are not highly valued locations.
- There is a need for ecosystem-based management strategies that are effective at conserving both the source and the output of services and a need to further understand the environmental system. Many of the general ecological principles are inter-related as are many of the goods and services. It is therefore extremely difficult or impossible to manage many of the services individually. The Ecological Principles Approach framework can be used to determine which services can be managed individually and which require integrated management.
- Considering which principles are interrelated with which services, can be used to highlight areas where managers require more information to manage effectively and to assess potential risks of management strategies.

- Improvements in the ability to recognise the economic value of services (Constanza et al. 1997, Beaumont et al. 2007) will be useful to justify and support management decisions. This is because increasing the provision of ecological services has a cost and many of the benefits are not currently or easily valued.
- Other potential methods for assessing values of ecosystem goods and services could arise from a combined approach of ecological and social research. Such research could quantify different aspects of environmental and functional changes with any associated changes in value e.g., through stated preference modeling.

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