THE MANY USES AND VALUES OF ESTUARINE ECOSYSTEMS

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ABSTRACT: Estuaries are complex ecological systems that mark the transition between fresh water and the open coast. They cover a diverse cross section of habitats supporting a wide range of human activities and values and are an integral part of the cultural identity of New Zealanders. Ecosystem services derived from estuaries range from benefits from food production and recreation opportunities to contaminant processing and cultural identity. The diversity of estuarine goods and services, and the ability of ecosystems to maintain them, is reliant to a large degree on a suite of ecosystem processes and the diversity of habitats within estuaries. Connections between habitats within estuaries are also important as goods and services are not always utilised or valued in the same locations as the ecological processes that underpin them.

Estuaries do not only provide goods and services for use within estuaries. Collectively the activities of estuarine organisms significantly influence the nature and rate of biogeochemical processes that sustain the biosphere. The shallow, comparatively warm, sunlit, well-mixed waters and extensive soft-sediment habitats of estuaries are often considered to play significant roles in processing contaminants from land and fuelling productivity on the adjacent coast. Fish live within and pass through estuaries, either to spawn in rivers or to spend their adult life in the open sea.

Many services are generated by different combinations of ecosystem processes, interacting over different space and time scales. These interrelationships make it difficult to isolate underpinning ecosystem processes, and highlight the potential for unintended consequences when management focuses on the delivery of single services with no cognisance of connectivity. For example, despite the fact that water flows downhill carrying many contaminants with it, estuaries are generally not comprehensively considered in freshwater management schemes. The complex relationships governing the delivery of services suggest that a precautionary management approach is necessary to prevent critical failure in service delivery. However, despite the long list of potential stressors and the need for restoration in some locations, our estuarine ecosystems still exhibit high biodiversity values.

The wide range of human uses of estuaries, together with the number of people living beside them, means that inevitably not all activities can be supported everywhere. This dilemma is a major environmental challenge for New Zealand and most other countries with coastlines. The inevitability of trade-offs must focus us on understanding the ecosystem processes behind service delivery and the threats to them, so that we can balance trade-offs and avoid, remedy or mitigate damage to this natural infrastructure. Most of our major cities are located beside estuaries and these ecosystems have served us well in terms of transport, trade and the provision of food. Estuaries also represent some of our most iconic tourist destinations and are areas of high economic value for coastal real estate. Many of these economic activities have been valued in monetary terms, but little attention has been paid to the underpinning ecosystem services that support these activities. As yet there is no national or regional stocktake of these services. Nevertheless, our current knowledge allows ecosystem services to be used to help communicate the benefits of maintaining ecosystem resilience and discuss trade-offs in conflicting resource use.

DEFINITION OF ESTUARIES

Estuaries are transitional environments, the meeting place of land, freshwater and marine ecosystems. New Zealand has an extensive shoreline (about 18 000 km) that includes more than 400 estuaries, collectively covering about 5300 km^2 (Hume and Herdendorf 1993). The transitional nature of estuaries makes them hard to define, but they are generally considered to be tidally influenced water bodies largely enclosed by land in which there is a measurable dilution of seawater due to freshwater inputs from rivers and runoff. Thus all of our harbours and much of our iconic coastline are, by definition, estuaries. New Zealand has a wide diversity of coastal land forms ranging from the fiords of south Westland (e.g. Doubtful Sound), to drowned river valleys (e.g. Hokianga Harbour), to lagoons (e.g. Okarito) (Figure 1). Our biggest harbours are Kaipara and Manukau, although much of the Hauraki Gulf can be defined as an estuary. Areas within estuaries that fall between the high and low tide marks are exposed and inundated during the rise and fall of the tide. These intertidal flats and reefs are particularly important to ecological processes in estuaries and often occupy a large part of the estuary.

Particularly in deep estuaries, such as fiords and sounds, strong vertical gradients in salinity add to habitat variability, with fresh water at the surface and salty water near the bottom. Stratification is more typical of deep estuaries fed by large rivers, whereas shallow estuaries are usually well mixed from surface to bottom, especially if most of the estuarine water volume drains out of the mouth on each outgoing tide. Salinity patterns affect the distributions of organisms living in the water column and on the seabed. The distribution and mixing of fresh and salt water, and patterns of retention within the estuary, affect the fate of materials coming from the catchment and their positive or negative effects on estuarine and adjacent coastal marine ecosystems.

The fresh water entering estuaries can contain large quantities of sediment eroded from coastal catchments and stream banks. This material ranges in grain size from coarse gravel to fine silts and clay. The finer sediments are easily transported and play an important role in influencing the relative proportions of sandy and muddy sediments within an estuary. They can also lead to marked reductions in water clarity in the upper reaches of estuaries, with the water appearing distinctly turbid. As the fresh water meets saltier water, the individual particles of fine sediment begin to flocculate (stick together), forming larger clusters that sink quickly to the bed. As many types of contaminants (particularly metals such as arsenic, mercury, copper, lead and zinc) bind to fine sediment particles, it is important to identify turbidity fronts and depositional zones where sediments settle. Like flocculation, the binding

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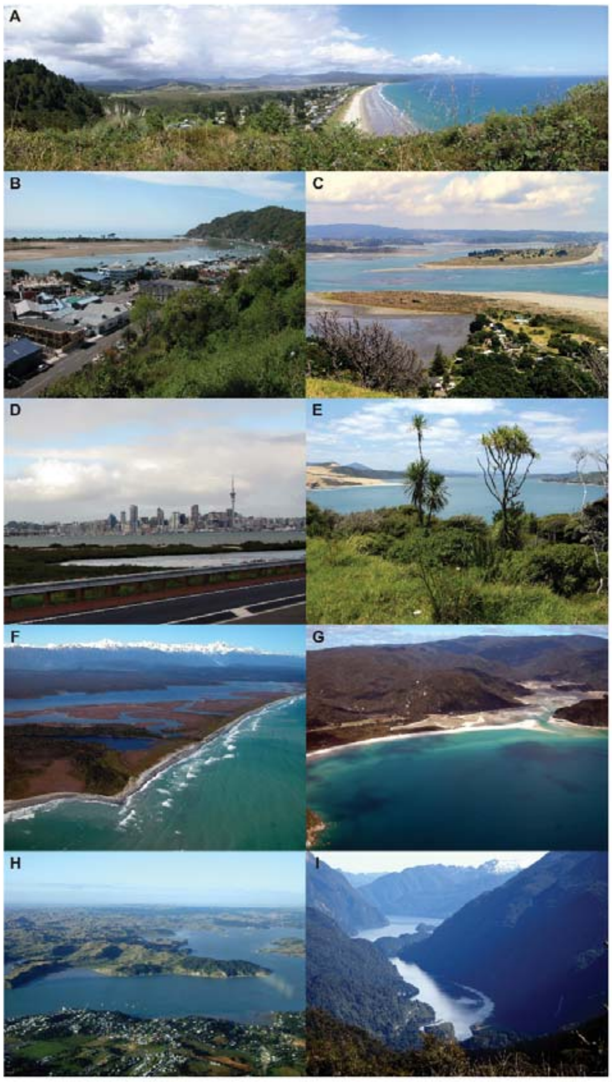

FIGURE 1 Estuary types of New Zealand. (A) Whangapoua Harbour, Coromandel Peninsula. [Simon Thrush, NIWA]; (B) Whakatane, Bay of Plenty. [Terry Hume, NIWA]; (C) Ohiwa Harbour, Bay of Plenty. [Rob Bell, NIWA]; (D) Waitemata Harbour, Auckland. [Simon Thrush]; (E) Hokianga Harbour, Northland. [Simon Thrush]; (F) Okarito Lagoon, West Coast. [Terry Hume]; (G) Awaroa Inlet, Nelson/Tasman region. [Terry Hume]; (H) Whaingaroa Harbour, Waikato. [Alistair Senior, NIWA]; (I) Doubtful Sound, Fiordland. [Joanne O'Callaghan, NIWA].

FIGURE 2 Diversity of estuarine habitats in New Zealand. (A) Intertidal sandflat with hummocky sediment, Manukau Harbour. [Simon Thrush, NIWA]; (B) Muddy sediment with established mangroves and pneumatophores, Whau Estuary, Waitemata Harbour. [Carolyn Lundquist, NIWA]; (C) Intertidal sand flat with seagrass and mangroves, Wharekawa Harbour, Coromandel. [Simon Thrush]; (D) Sandy sediment with shell hash and a rocky reef habitat in the background, Bay of Islands. [Sarah Hailes, NIWA]; (E) Muddy sediment (depth of mud shown by a footprint in the foreground) and mangroves, Whangateau Harbour. [Sarah Hailes]; (F) Highly rippled, sandy sediment with tubeworms visible, Bay of Islands. [Sarah Hailes]; (G) Subtidal shell hash and algae, Whangapoua Harbour. [Simon Thrush]; (H) Subtidal with high diversity of organisms, including tubeworm mats and scallops, Mahurangi Harbour. [Simon Thrush].

of contaminants to sediment particles is affected by salinity, thus the exposure of organisms to these substances will vary spatially and temporally in an estuary in accordance with salinity.

New Zealand's topography and climate mean that most of our rivers and streams are short, resulting in highly variable freshwater inflows. These features, along with our tidal range (varying from about 0.2 to 4.2 m around the country), which supports exchange with the coastal ocean, mean that almost all of our estuaries are close in salinity to the coastal ocean, most of the time. Consequently, the majority of organisms that utilise our estuarine habitats are marine species.

BIODIVERSITY OF ESTUARIES

Biodiversity and ecosystem services are intimately linked. Biodiversity encompasses the variety of life and its interaction with the environment, ranging from genotypes to ecosystems. Dominated by marine organisms, our estuaries are diverse and contain representatives of a wide range of phyla from microorganisms to whales. On the intertidal sandflats of the estuaries around Auckland we can easily collect 200 species of organisms big enough to see with the naked eye. By marine standards estuaries are generally considered species-poor ecosystems. Nevertheless, the resident species, the strong physical and chemical gradients found within estuaries and the supply of nutrients from the adjacent catchment make estuaries functionally diverse.

Generally speaking, the fresh water entering an estuary has nutrient concentrations (e.g. forms of nitrogen and phosphorus, such as NO_3^-, NH^{4+} and PO_4^-) that are several times higher than those of adjacent coastal seawater. Thus, the retention of nutrient-laden fresh water in a semi-enclosed estuary provides an opportunity for primary producers to flourish, particularly in shallow surface waters where the sunlight is brightest and the water is warm. Some of this primary production will be utilised by primary and secondary consumers within the estuary and some may be exported to the adjacent coast.

Seawater does not simply flow in and out of an estuary with the tide. The speed and direction of tidal currents at the estuary entrance are affected by the narrowness and depth of the mouth and can be deflected and altered by sandbanks, rocky outcrops, shoreline contours, engineered structures and biogenic reefs. As a result, planktonic organisms are often concentrated in distinctive fronts or eddies. These areas, which may be either stable or fleeting features, are often sites of heightened feeding activity by planktivorous fishes and their predators, including larger fish, birds and marine mammals. Thus, because the distribution of water-dwelling organisms in an estuary is highly variable in space and time due to steep gradients of nutrients, turbidity, productivity currents and salinity, abundance and diversity can be extremely high.

Across New Zealand, there is a great range of habitats found on the floor of estuaries, from the terrestrial fringing habitats of saltmarsh and mangrove to the deep-water muddy basins at the bottom of the fiords. There is more to the description of estuary floor habitats than rock, sand and mud. Just like terrestrial habitats, estuarine habitats are most informatively defined based on dominant and habitat-structuring species. These habitats can include tube mats, scallop beds, oyster reefs, crab-burrowed mudflats, cockle beds, mussel beds, sponge gardens, kelp reefs and turfing algae (Figure 2). These descriptive habitat designations often give us clues as to dominant ecological processes that underpin the delivery of ecosystem services.

Many species fundamentally influence ecosystem processes by altering the physical architecture of the sediment on the estuary floor. Organisms – and their burrows, mounds and tubes – modify flow over the seafloor and provide settlement sites and refugia from predators. On the sediment surface, predators (e.g. rays, birds, fish, starfish and crabs) digging into the sediment in search of food create pits, adding to the heterogeneity of the seafloor. Microscopic algae and polychaete tube mats tend to bind the sediment surface, while the movement of animals crawling over the surface tend to increase sediment erodibility. Below the sediment surface, physical structures such as tubes and burrows, and the activities of animals that affect the movement of particles and pore water, further influence habitat heterogeneity and many important microbial and geochemical processes. Microbes in the sediments drive nutrient and carbon cycling, but this is strongly facilitated by the movement, burrowing, hydraulic pumping and feeding of animals living both on (epifaunal) or within (infauna) the sediment. These processes highlight important links between seabed and water-column ecosystems that affect nutrient recycling, the processing of organic material and carbon storage. Collectively, these ecosystem processes support a wide range of services, but often it is difficult to untangle the relative contributions of different process, habitats or species in service delivery (Figure 3).

Estuary-floor habitats typically form a mosaic of patches within major gradients associated with salinity, wave and tide energy and depth, as well as the biological processes that generate these landscapes. This patchiness in habitats and the connectivity between them makes a very important contribution to the delivery of estuarine ecosystem services. Many organisms shift in their use of habitat, either daily or as they grow, balancing access to food resources against the risk of predation or utilising a series of different food resources (as their size increases and their energy requirements change). Thus, many of the species of shellfish and fish that we value are supported by a range of habitats within the estuary. As mentioned above, primary productivity in one part of the estuary may be important in fuelling secondary production in other parts of the estuary. This connectivity between habitats is not only important in maintaining basic ecosystem processes that support service delivery, but also forms part of the aesthetic and cultural services.

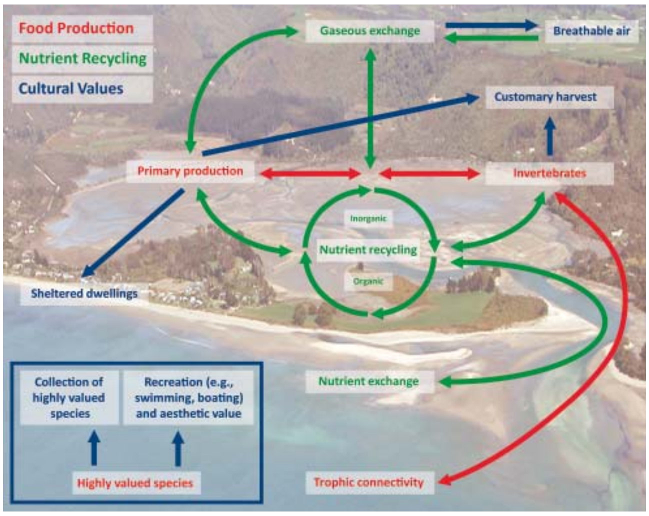

FIGURE 3 Estuarine ecosystem services are underpinned by multiple ecosystem functions operating over a range of spatial and temporal scales. Individual functions can underpin several services, leading to high connectivity and interdependence. The figure demonstrates the interconnections within an estuarine coastal system between the cycling of nutrients, the production of different foods, and cultural attributes valued by society. Estuary: Parapara Inlet, Golden Bay. [Terry Hume, NIWA]

Rapid rates of biodiversity loss have raised concerns for the effect on ecosystem processing and, by natural extension, the provision of ecosystem services (Balvanera et al. 2006; Airoldi and Beck 2007). Globally, 60% of ecosystem services are deteriorating or are already overused (Millennium Assessment 2005), emphasising the need to protect biodiversity levels for sustainable use. There is also growing recognition of positive relationships between aspects of biodiversity and many ecosystem processes (Solan et al. 2004; Stachowicz et al. 2008). Fundamentally, species diversity is needed to maintain functional diversity, which results in more-complete resource use and provides resilience and temporal stability through functional compensation (Walker et al. 1999). In supporting the delivery of ecosystem services, biodiversity affects key processes as well as having its own intrinsic value. Positive diversity effects have been associated with nutrient cycling and productivity and for maintenance and supporting services (Balvanera et al. 2006); however, these relationships are often non-linear and context dependent. Any overarching relationship is complicated by the division of services into individual units, where some may be highly dependent on biodiversity and others are supported by a limited number of species or a single functional group. These complex relationships create uncertainty in the exact role of biodiversity and suggest that a precautionary management approach may prevent critical failure (Daily et al. 2000).

SERVICES FROM ESTUARIES

Estuaries are complex ecological systems that provide many essential goods and services underpinning a wide range of human uses and values. The services in Table 1 are grouped into four broad categories:

- Provisioning services describe the array of extracted products.
- Regulation and maintenance services describe the fundamental life-supporting capacity that the environment delivers.
- Habitat and ecological community services describe the structural role that organisms afford.
- Cultural services describe social aspects and the improvement to quality of life.

The estuarine services we discuss are those that involve biological processes. We have not considered services that are derived from purely physical processes (such as tidal power generation or the navigability of waterways). Services cover benefits from food and recreational opportunities to the more obscure such as the provision of genetic resources. There are those that we rely on every day and others that are only invoked in times of trouble, such as storm protection.

There are many examples of specific ecosystem processes that directly link to service delivery. However, often what appear to be quite simple service deliveries are in fact generated by multiple ecological processes and interactions that contribute to a range of different services. These overlaps and interrelationships make it difficult to isolate processes or services and highlight the potential for unintended consequences when management takes a singular or sectorial approach with no cognisance of the connectivity. The balancing of uses requires careful management and, although it is useful to define and isolate individual services, their connections and high level of interdependency favours a systems approach to their management. In the next section we illustrate the services provided by estuaries and show examples of the underpinning ecological processes identified in Table 1, together with connections between multiple processes and multiple services.

Provisioning services

Production of food — Perhaps one of the most widely recognised services provided by estuaries is the production of shellfish and fish, harvested by cultural, recreational and commercial fishers, and aquaculture. Many species of shellfish reside in estuaries (e.g. scallops, pipi and cockles), often exploiting different habitats at different life stages. Many species of fish also utilise our estuaries; some are permanent residents, others use the estuary to breed or as juvenile nurseries. This includes many commercially and recreationally important species such as snapper and blue cod.

High productivity in estuaries attracts high numbers of fish, shorebirds, seabirds and marine mammals. These species are often top predators and changes in their numbers can impact the density of middle-foodweb predators or species that play important roles in other community or ecosystem processes (Thrush et al. 1994). Many of these are migratory species demonstrating not only the transfer of energy up the food chain that occurs in healthy ecosystems but also the potential for its subsequent export across the globe. For example, the inner Firth of Thames covers a large area of exposed intertidal flats and is listed as a RAMSAR site (internationally recognised wetland area) due to its importance as roosting and feeding habitat for migratory shorebirds.

Production services in estuaries are underpinned by multiple ecosystem processes starting with primary productivity, and the underlying processes controlling nutrient recycling and water clarity (Table 1). However, connectivity between habitats and within foodwebs is also needed to transfer energy towards higher trophic levels. Most species require specific habitats, for example shorebird populations are supported by low-tide feeding grounds as well as the presence of high-tide roosting areas. In turn, these wild populations of birds, fish, shellfish and mammals provide cultural services, aesthetics, amenity values and the potential for knowledge generation.

Production of raw materials — Estuaries provide materials that are useful for many purposes other than direct human consumption. Vegetation is used as fertiliser, fish-food and grazing for livestock. Traditional uses include Maori pōhā (kelp bags) used for storing and transporting food. Shells are used for ornamentation, in food preparation, as musical instruments and as a source of artistic inspiration.

TABLE 1. Estuarine ecosystem services, their overarching categories and underpinning processes

Services category	Services	Roles contributing to these services
Provisioning services	Production of food Production of raw materials Production of medicines and pharmaceuticals	Primary production Secondary production Trophic relationships Reproductive habitats Refugia for juvenile life stages Ontogenetic habitat shifts Biogeochemical cycles associated with nutrient supply Biogenic habitat Biodiversity
Regulation and maintenance services	Regulation of waste assimilation processes Storing and cycling nutrients Gaseous composition of the atmosphere and climate regulation Sediment formation and stability Maintaining hydraulic cycles and shoreline protection	Biogeochemical cycles Storage and processing Benthic–pelagic coupling Bioturbation/irrigation Molluscs, corals and other calcimass generators Shell formation and bivalve abundance Biogenic structure / reef-makers Fringing vegetation Bioturbation and burrow formation Species, spatial structure, size and density influences on hydraulic processes
Habitat and ecological community services	Provision of habitat structure Resilience Genetic resources	Invasibility Provision of habitat Maintenance of trophic structure Biodiversity Resource use complementarity Facilitation Allee effects
Cultural services	Cultural and spiritual heritage Recreation and tourism Aesthetics Cognitive benefits Non-use benefits Speculative benefits	Ecosystem, community and population processing Processes influencing water clarity, habitat diversity Biodiversity

Production of medicines — Chemicals extracted from estuarine-dependent species are being used in pharmaceuticals, nutraceuticals and in pest control. New Zealand examples include chemicals currently being tested in anti-cancer research, agar, kelp powder, chitin, fish oil, calcium powder, fucoidin sulphate, green-lipped mussel extract, and collagen.

Regulation and maintenance services

Regulation and maintenance services are the biophysicochemical processes that sustain life-support systems and underpin other ecosystem services. They play an important role for humans, producing the air we breathe, maintaining system integrity and mitigating human impacts. The ecological processes that underpin this wide range of services are also extremely diverse. However, processes involving plants and animals that live on or in the seafloor and their activities that elevate chemical exchange processes are particularly important to the maintenance of these services.

Regulation of waste — Transformation of waste materials and the removal of pollutants are influenced by estuarine organisms in a number of ways including binding, sequestration and burial. Bacteria in sediments are involved in detoxifying heavy metals. Some species of shellfish sequester heavy metals, lowering toxicity to other organisms, but potentially raising exposure risk to humans and other predators. Organic wastes, such as sewage, are utilised as energy sources and broken down through a combination of plant, animal and microbial activity. In healthy ecosystems these food resources are then transported across the foodweb. As many of these services are related to the way organisms transform energy and matter, if waste levels exceed the assimilative capacity of the ecosystem then service delivery will catastrophically fail.

Storing and cycling nutrients — Organic and inorganic nutrients are stored, cycled and transformed by the activities of estuarine species. Nutrient recycling is undertaken in both the water column and the sediment, but in most estuaries sediment processes are particularly important. Animals moving within the sediment (bioturbation) affect pore water flows, stimulating microbial processes and enhancing the rate at which organic matter can be broken down and nutrients remineralised. Bioturbation can also destabilise chemical gradients in pore water, affect sediment permeability and erodibility, subduct organic matter, influence decomposition rates, and release inorganic nutrients from sediments to overlying waters. Collectively, these processes maintain the supply of essential nutrients such as carbon, nitrogen, phosphorus, sulphur and metals. Recycled nutrients supply a significant proportion of the nutrient demand for primary production, and the form and rate of nutrient supply to the phytoplankton may be a factor influencing risk of harmful algal blooms.

Climate regulation — Estuaries contribute to the regulation of climate through the exchange of gases between the water, sediments and atmosphere. This includes the balance of oxygen and carbon dioxide and the regulation of several greenhouse gases. The open ocean is generally recognised for its contribution to climate regulation because of its vast area. Although collectively covering a small area, estuaries make a disproportionally large contribution because of the high rates of gas exchange. All estuarine primary producers take up carbon dioxide for photosynthesis; however, large vegetation, such as mangroves and seagrass, provide a notable standing stock and present longer-term storage.

Carbon sequestration is an important service mitigating the increased rate of climate change due to anthropogenic emissions (Nellemann et al. 2009). While economic markets exist for this service in terrestrial ecosystems, there is no such accounting in estuarine and marine ecosystems. This is a lost opportunity for a country like New Zealand with such an extensive coastal and marine estate. Saltmarsh, mangrove forests and seagrass beds provide carbon sequestration roles in New Zealand estuaries. Seaweeds (e.g. kelp forests) also provide a role in carbon sequestration, though the storage potential for material that is not advected to the deep ocean is not well understood. Vegetated coastal habitats are estimated to contribute half of the total carbon sequestration in ocean sediments, though they cover less than 2% of the ocean surface (Lafoley and Grimsditch 2009). A significant proportion of carbon sequestration in estuaries occurs in biomass stored in sediments, with rates of long-term carbon accumulation in sediment estimated at 10 and 50 times that of temperate and tropical terrestrial forests, respectively (Lafoley and Grimsditch 2009).

Another important service provided by estuaries is the processing of terrestrially derived nutrients and the net loss of nitrogen to the atmosphere. Denitrification is the main mechanism of removal of nitrogen from estuarine systems. It is a biogeochemical process where dissolved forms of inorganic nitrogen (NH^{4+}, NO_3^- and NO_2^-) are converted into molecular nitrogen gas (N_2) and the greenhouse gas nitrous oxide (N_2O). Denitrification occurs only under anoxic conditions, and is mediated by specialist bacteria present in sediments (2 to 20 mm beneath the sediment surface). The degree to which sediment-dwelling animals influence rates of nitrogen removal is not yet well understood. What is clear, however, is that biogeochemical interactions among an array of sediment-dwelling organisms (e.g. bacteria, microalgae and macrofauna) are central to this important ecosystem service.

Most New Zealand estuaries are not yet badly affected by excessive loadings of nutrients and organic matter, nevertheless, this is a significant environmental problem in many overseas estuaries and the permanent removal of excess nutrients from estuaries is a valuable ecosystem service. When the nitrogen loading becomes excessive, eutrophication leads to increases in the release of nitrous oxide and methane, both greenhouse gasses, thus indicating critical thresholds in service delivery. This service will become increasingly crucial to New Zealand in the future.

Sediment formation and stability — Animals that make shells out of calcium carbonate, in particular bivalves and snails, provide an important service in sediment generation. Worldwide there has been substantial loss of shellfish in coastal ecosystems due to human activities (Airoldi and Beck 2007). These shells and shell fragments (hash) can persist in sediments over century-to-millennial timescales, affecting the physical heterogeneity of the sediment, biogeochemical processes, and species richness and β-diversity (Thrush et al. 2006). The proportion of carbonate material can be substantial in some coastal ecosystems (e.g. Hilton (1990) indicates that some sediments off Pakiri Beach, north of Leigh, are in excess of 60% carbonate). This shell material in the sediment can have important effects, enhancing biodiversity, decreasing rates of predation, and providing a pool of sediment carbonate that may provide an important buffer to the effects of ocean acidification. Estuarine and coastal species also play a role in the generation of beach sediment.

Estuarine vegetation and organisms can affect the physical stability of their environment. The activity of some animals, particularly those that dig holes in the sediment to feed or move across the sediment–water interface, tend to locally destabilise sediments making them prone to resuspension and transport by tides and waves. Conversely, organisms that produce shells that lag the sediment surface, or create reefs, can have important stabilising effects. Sediment stabilisation is complex and depends on many factors including organism identity, density, and the sediment grain size and physical forcing. In sufficient densities plants like mangroves and seagrass, and biota such as worms and crabs that build structures, prevent the erosion of sediment and increase deposition rates of organisms or sediment suspended in the water.

Sediment can also be stabilised by sediment-dwelling microalgae. This frequently results from a balance between bioturbating animals disturbing the sediment and releasing nutrients and the resultant growth rate of the microalgae.

Shoreline protection — Fringing vegetation, such as mangroves, salt marshes, and coastal scrub can retain water (like a sponge) and control its release. While this may be beneficial to downstream systems, it slows drainage upstream. Vegetation and biota also protect the shoreline during storms by dissipating wave and tidal energy and reducing the impacts of tidal surges and storm events on the shoreline and adjacent properties. Within the estuary, the formation of intertidal and shallow subtidal sand bars often involves species that stabilise sediments, and can offer protection to the shoreline. Shells lagging the estuary floor can play an important role in stabilising the channel bed in the throat of tidal inlets on mobile sandy shores (e.g. at the mouth of Whangateau Harbour).

Habitat and ecological community services

Provision of habitat structure — The provision of biogenic habitat structures is of paramount importance and a prerequisite for the provision of many goods and services. Many estuarine plants and animals provide habitat structure that is exploited by other species. This provides nursery grounds for juvenile organisms, refugia for predator avoidance and permanent habitat structure for many species. Important New Zealand examples include seagrass meadows, shellfish beds, subtidal reefs, sponge gardens and kelp forests. Mangroves play an important role, although their often small stature and the small amount of time they are inundated by water in New Zealand appear to limit their importance in some estuaries. Again, while the habitat structure may be utilised only by species living within the specific estuary, it may also be used by migrating and transitory species. For example, New Zealand estuarine flats provide critical habitat for migratory seabirds such as bar-tailed godwits and knots as well as species like oystercatchers, herons, banded rails and wrybills

Resilience — Just as biodiversity can be directly valued as a service, so too can resilience. Ecological resilience theoretically represents change of an ecosystem within and between different states and reflects the ability of a system to maintain its identity in the face of both internal drivers and external change (Cumming et al. 2005; Walker and Salt 2006). These states often represent conditions that are good or bad from a specific perspective. Thus high resilience for a system that is in a 'good' state (e.g. in terms of the delivery of a particular ecosystem service) represents an insurance against potentially adverse changes. For example, high rates of bioturbation by urchins have been shown to reduce colonisation by non-indigenous species in estuarine sediments (Lohrer et al. 2008). However, the ecosystem processes that generate resilience also can result in slow recovery to more valued states, when thresholds are exceeded (Scheffer et al. 2001). For example, macrobenthic communities in degraded estuaries are dominated by small, rapidly growing and highly mobile species and typically have low functionality. These communities are quick to recover from disturbance, but often slow to return to a more valued state (Thrush and Whitlatch 2001).

Genetic resources — Healthy ecosystems contain a 'genetic library' of species (De Groot et al. 2002). These genetic resources can be exploited for human gain with applications in drugs, pharmaceuticals and aquaculture. For example, in fish farming, genetic resources have been exploited to develop genetically superior brood stocks with enhanced growth rates and feed conversion efficiencies, improved disease resistance, and increased tolerance of cold and low oxygen conditions (Moberg and Folke 1999; Rönnbäck et al. 2007). Genetic resources play a role in many other services, as maintaining genetic diversity ensures that communities contain the broadest possible functional diversity – which may prove critical in the ability to respond to environmental change.

Cultural services

In addition to the essential life services listed above, healthy estuaries contribute to human well-being and provide a number of social and amenity services. Estuaries are easily accessed and have multiple and diverse usages that contribute to the quality of life and have significant economic value (Daniel et al. 2012). For many iwi, harbours and estuaries provide a profound source of identity and spiritual well-being and a concomitant sense of responsibility (Penny 2007).

Cultural and spiritual heritage — As the transition between land, rivers and the sea, estuaries are easily accessed and have multiple and diverse usages. Maori culture-spirituality and estuaries are tightly linked, not only as a place for food gathering. Often marine and estuarine products take on particular cultural significance: for example, fish hooks created from Cook's turban shells; scrapers and cutters produced from mussel shells; tusk shells used in anklets and necklaces; pieces of pāua shell inlayed in wood or bone carvings, often representing eyes; and *Dosinia* and scallop shells used to hold pigments for tattooing (Wassilieff 2010). The proximity of population centres to harbours and estuaries has entrenched a strong connection between the marine environment and the country's cultural and spiritual heritage. Many quintessential 'kiwi' activities involve being in, on, or around the water and drive our customs, practices and values.

Recreation and tourism — Recreation is one of the most readily identifiable and highly valued uses of estuaries: ranging from sailing, boating, wind surfing, water skiing, swimming and diving, –which involve direct water contact, to bird watching, walking the dog or passively reclining on the beach. These broad uses are underpinned by many different ecological processes that maintain aesthetic, landscape and ecological values, and water quality.

Aesthetics — Estuaries, harbours and seascapes are often visually appealing and their scenic qualities are highly valued. The beauty of the natural environment increases human well-being and can have a positive impact on property prices and land value in desirable locations.

Cognitive benefits — This refers to the value of estuarine resources that stimulate cognitive development, including education and scientific research. Derivatives from this are that information 'held' in the natural environment can be adapted, harnessed or mimicked by humans, for technological and medicinal purposes. Examples include the use of polychaete worm spines in the photonic engineering and communication technologies (Parker et al. 2001) and the development of wear-resistant ceramics from studying bivalve shells (Ross and Wyeth 1997).

Non-use benefits — These are sometimes called 'feel good' or 'warm glow' benefits that are derived from an estuary or estuarine species despite the fact that they are unlikely to be utilised or experienced. This includes 'existence value', the contentment derived in the knowledge that an ecosystem contains a natural resource or species, and 'bequest' value, the importance placed in the availability for future generations. For example, we may place value in fiords for supporting different corals even if we do not get to see them.

Speculative benefits — Option use value is the willingness to safeguard estuarine resources that are not currently used but are anticipated to be exploited in the future. This is termed a speculative benefit when the exact nature of the benefit is unknown but the value of protecting potential resources is recognised. In other words, this is the value of being able to change one's mind, and of keeping one's options open. Speculative and option use benefits are intrinsically linked with biodiversity. If biodiversity declines, the future options will also decrease (Beaumont et al. 2008).

RESEARCH, MANAGEMENT, AND COMMUNICATION ABOUT ESTUARINE SERVICES

We have so far focused our description of ecosystem services on the underpinning ecological processes and linked this to societal values. However, an important role for ecosystem service thinking is in allowing for communication of concepts (Granek et al. 2010). Ecosystem services offer us a way to address complex, complicated and contentious problems because they render the links between natural systems and human well-being explicit. In turn, this enables the assessment of the complex feedbacks and trade-offs that occur among services and human beneficiaries, and incorporates values into decision-making (Daily et al. 2009).

Many recent critiques of the ecosystem services approach have focused on the challenges associated with integrating social and scientific knowledge into governance structures in meaningful ways (Cook and Spray 2012). These challenges often arise because of difficulties with defining clear, simple, causal links between what society values in an estuary, how those values are prioritised and traded off against each other, and the underpinning foundational processes of ecosystem service identification, valuation, and mapping (Tallis and Polasky 2011). The importance of these framing issues to the use of ecosystem services as a mode of communication or a path to monetary or non-monetary valuation should not be underestimated. Tensions arise in this area because the ecosystem service framework is largely derived from a scientific perspective (Cook and Spray 2012), but its implementation calls for new, interdisciplinary or transdisciplinary methods of application (Carpenter and Folke 2006; Carpenter et al. 2009). This should include the extensive involvement of stakeholders (Stringer et al. 2006).

Participatory and co-learning processes that are essential to the resolution of many environmental issues require that participants are able to look beyond narrow sectarian interests, at least to acknowledge that others' opinions exist, to translate their concern into an action. This is especially pertinent in the case of estuaries because they have such a wide range of uses and values. The inability to recognise trade-offs among services in decision-making can result in unintended consequences (Daily et al. 2011) such as the failure to manage resources adequately, or the development of inappropriate policies (Rodríguez et al. 2006). In this setting, scientists and resource managers need to communicate with community members about the local values of the area, and to consider this important context when developing plans and policies. In turn, community participants need to learn to articulate their values and passions in a way that can be translated into an ecosystem services framework by resource managers and scientists. This process of co-learning can help resolve what needs to be managed, to maintain a wide range of values. However, the union of these previously disparate forms of knowledge and power is unlikely to occur without a great deal of experimentation and struggle (e.g. MacMynowski 2007; van Wyk et al. 2008).

DRIVERS OF CHANGE

Estuaries represent important meeting places between the land and sea and consequently are subjected to multiple and cumulative stressors. Despite the long list of potential stressors and the need for restoration in some locations, our estuarine and coastal ecosystems still exhibit high biodiversity values and are critical to our tourism industry and our sense of national identity.

Rivers, streams, drains and direct runoff from land bring a variety of contaminants to our estuaries and coasts. Modification of coastal and estuarine shorelines through reclamation, dredging and in-water structures (e.g. causeways, bridges, piers, marinas and structures associated with aquaculture) can also affect ecosystem process and as a result service delivery; while from the sea we bring stressors associated with fishing, mining and invasive species. The health of our estuaries is closely linked to the range and quantity of the services they provide, which in turn feeds back across multiple societal values and human well-being (Figure 4).

Estuaries have played a key role in the colonisation of New Zealand and the development of our economy and society. Similar to most countries, many of our major cities are situated on harbours and these are areas of high urban growth. In 2006, 65% of New Zealanders were living within 5 km of the coast and 75% within 10 km. While proximity to the coast differs between regions, those regions with higher concentrations of people living near the coast have also tended to show stronger trends in population growth (Statisitics New Zealand no date). New Zealand has certainly had serious local problems with industrial contaminants in our estuaries (Fox et al. 1988; Ministry for the Environment 2011); however, many of our contaminant problems are more insidious and are derived from diffuse sources such as urban

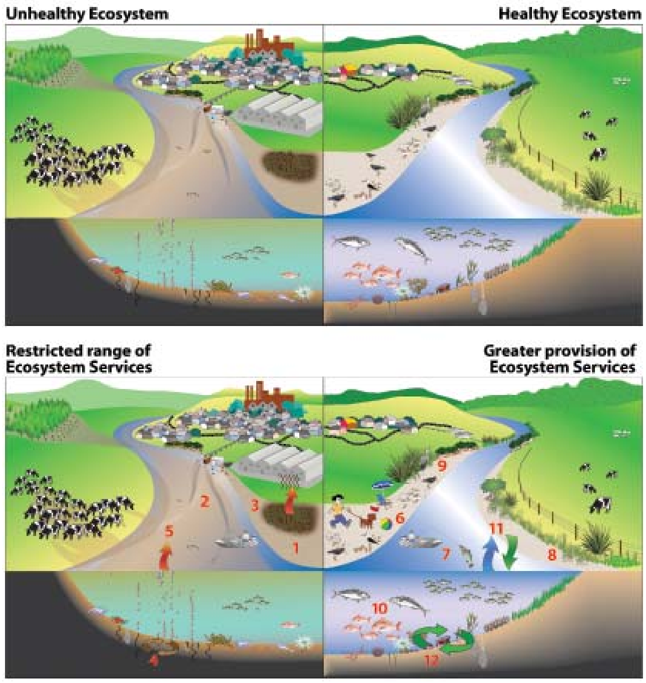

FIGURE 4 Healthy estuaries provide diverse ecosystem services relative to their unhealthy counterparts. Many ecosystem services in healthy estuaries work to ameliorate the effects of human impacts whereas in degraded estuaries both the number and value of services are reduced, which often exacerbates adverse effects. Unhealthy systems are less attractive for recreation due to increased muddy sediments and turbidity (1), effluent from the land carrying pathogens or toxic substances (2), and periodic incidents such as rotting nuisance seaweed blooms (3). Nutrient recycling is restricted due to the absence of mature benthic species and a lack of oxygen in the sediments (4). This can lead to greenhouse gas release (5). In contrast, healthy systems are cleaner, offering wider and enhanced recreational opportunities (6), better food resources (7), and the retention of sediments (8), providing coastal protection (9). Food webs contain many links and large predators are present (10). Healthy waters are supported by balanced gas (11) and nutrient (12) exchange.

runoff. Contaminant concentrations are often highest in muddy sediments and in highly urban and light industrial areas, but even low levels of urban contaminants can change ecosystem process (Lohrer et al. 2011).

Profound changes to estuarine ecosystems have been wrought by the runoff of terrestrial sediment. New Zealand is a tectonically active country where steep landscapes, short and flashy rivers and intense rainfall provide a naturally high potential for sediment to be transported and deposited in our estuaries and coastlines. Loss of native forest cover and other changes in land use have increased the rate of sediment entering our estuaries (Thrush et al. 2004). The consequences of these impacts seem to be stronger in estuaries than in the streams that feed into them (Reid et al. 2011; Rodil et al. 2011). Much of the sediment entering estuaries is composed of silts or clays that react chemically with seawater and deposit to the estuary floor, smothering resident organisms, changing habitat characteristics and affecting many of the ecosystem processes that underpin service delivery. Much of this deposited material is resuspended by tides and waves, leading to high suspended sediment concentrations affecting water clarity, impacting on primary production and suspension-feeding organisms.

Another stressor likely to be of increasing importance to our estuaries is nutrients. While the productivity of estuaries is high partly because of the input of nutrients from the land, you can have too much of a good thing and this leads to eutrophication. The signs of eutrophication in estuaries can involve the increasing frequency of phytoplankton blooms and, particularly in shallow estuaries, excessive growth of some seaweeds (e.g. sea lettuce) and ultimately loss of oxygen in the sediments leading to mass mortalities. In New Zealand most cases of estuarine eutrophication have involved sewage or abattoir waste, which have often been highly localised within individual estuaries (e.g. Manukau Harbour, Otago Harbour and Avon-Heathcote Estuary). However, nutrient loads are increasing with the intensification of farming in many areas and signs of future and serious problems are of concern (Heggie and Savage 2009). Internationally, the incidence of disease and the emergence of new pathogens are on the rise. These are often associated with eutrophication, and, in many cases, this coastal degradation has consequences to human health (Epstein et al. 1993). Episodes of harmful algal blooms are also increasing in frequency and intensity, directly affecting both the resource base and people living in coastal areas (Cloern 2001).

Estuarine systems are among the most invaded ecosystems in the world, with introduced species causing major ecological changes (Carlton 1996). Introduced organisms often change the structure of coastal habitats by physically displacing or grazing upon native organisms (Grosholz 2002). Waitemata Harbour (Auckland) has been invaded by as many as 70 non-indigenous species (Inglis et al. 2005). Post-introduction invasion success likely depends on many factors, including the health and diversity of the recipient ecological system. Ecosystems containing healthy and diverse assemblages may be more able to repel invaders, a concept known as 'invasion resistance', although, others suggest that factors promoting native diversity may also provide favourable conditions for new species (Stohlgren et al. 1999).

The specific effects of the individual stressors acting in a particular estuary will depend on several factors, but collectively they can be grouped into those factors that disturb resident populations, change habitats, modify foodwebs or change the fitness of individuals. Many of the major stressors in estuaries result in habitat change, either as a result of direct physical disturbance or through shifts in the distribution of species that are important in influencing biogenic structure (e.g. burrowing crustaceans and polychaetes, reef-forming bivalves and seagrass) (Thrush et al. 2004; Altieri and Witman 2006). A stressor can be considered as a factor that impacts on the fitness of individuals. This means that species abundance distributions across natural landscapes may be affected simultaneously by a number of anthropogenic and natural stressors. These stressors may not simply act in additive ways; rather, multiplicative interactions occur to either increase (synergistic) or dampen (antagonistic) the effects of stressors (Hames et al. 2006). Differing responses to combinations of stressors lead to uncertainty in the prediction of contaminant effects and ecological resilience (Breitburg et al. 1999).

Many ecosystems are affected by cumulative impacts that, although not individually catastrophic, collectively result in the loss and fragmentation of habitats and shifts in biodiversity, associated with the removal of habitat-specific or functionally important species. The successional processes that follow disturbance are the product of interactions within the disturbed area and the supply of recruits (Thrush et al. 2008a). A mosaic of patches with different environmental characteristics, at different states of recovery, can contribute to spatial heterogeneity and biodiversity within ecosystems. Human activity (e.g. habitat modification/destruction, pollution and eutrophication) increases the frequency and extent of disturbance to the point where disturbance-sensitive species and recovery-sensitive species (slow growth, reproductive output and dispersal ability) are selectively removed from the mosaic of patches. The cumulative effect of this incremental change in both the disturbance regime and the response of the resident communities across the landscape can result in unexpected, non-linear responses and profound changes in community structure and process, and decreases in resilience and biodiversity. Habitat loss, fragmentation and homogenisation of natural communities alter the patterns of connectivity, potentially isolating populations and communities and limiting them to suboptimal habitats (Crooks and Sanjayan 2006). Escalating degradative ecological change, due to alterations in disturbance regimes, has the potential to feed back onto both local and regional changes in ecological communities (Folke et al. 2004). Diffuse-source and multiple-stressor effects that gradually degrade or trip thresholds can undermine resilience and shift the system to different states (Scheffer et al. 2001).

Estuaries, like coral reefs, are especially prone to the effects of climate change (Kennedy et al. 2002). Climate change in an estuarine setting can only be realistically viewed through a multiple-stressor lens. With increased storminess and episodic rainfall we can expect changes in freshwater inputs and sediment runoff in many areas. In the estuary, temperatures and sea level are expected to rise, affecting habitats, species distributions and many of the processes that underpin provisioning ecosystem services. At the coast, changes in storminess, increased storm surge, changes in wave climate and changes in coastal productivity and coastal ocean currents are likely to affect estuarine ecology. Estuaries are also regions with high variation in water column pH; while this can be due to a number of natural factors it is exacerbated by both local anthropogenic stress and global climate change. All of these stressors interact with other future cumulative effects on the ecosystem. For example, profound eutrophication effects, such as decreased oxygen concentration on the estuary floor creating dead zones, while primarily influenced by nutrient loading is also affected by temperature- and salinity-induced water stratification that may also change with climate change. Furthermore, the eutrophication status of estuaries can feed back on climate change through the production of greenhouse gases. In highly polluted estuaries, receiving industrial and urban wastes, large quantities of carbon dioxide are released resulting in elevated pCO_2 (Frankignoulle et al. 1998). When the system becomes so polluted as to create dead zones, methane and N_2O are released to the atmosphere, both potent greenhouse gases. Cumulative effects such as these threaten the resilience of estuarine ecosystems.

Predicting the future is difficult and surprise often plays an important role in temporal change. This emphasises the importance of maintaining the resilience and adaptive capacity of our estuarine ecosystem. This requires an important shift in thinking away from simple command-and-control processes where we manage a system down to an ordained limit, to a more adaptive, inclusive and ecosystem-based approach where we focus on ensuring that the ecosystem has the best chance of maintaining its ability to cope with surprises. Important ecosystem services will be those that help ensure resilience and the processing of contaminants. These benefits from ecosystem services are more likely to be especially valued in estuaries that are subjected to multiple uses, such as urban estuaries, areas of intensive aquaculture and estuaries receiving high inputs of sediment and nutrients from rivers and streams.

ASSESSING ECOSYSTEM CONDITION AND TRENDS

Assessing the condition of ecosystem services in estuaries is an interesting challenge, with no methodology yet in place (Barbier et al. 2011). Many regional councils are presently grappling with this concept, while the Department of Conservation includes this aspect under its present focus on ecosystem 'integrity'. Ecological integrity is a holistic term that seeks to capture our sense of nature, its functionality and self-maintenance and the Department of Conservation has been seeking to operationalize this definition for marine monitoring (Thrush et al. 2011).

Ecosystem condition can be viewed either as a static or dynamic process and monitoring studies either focus on broad-scale surveys or on time-series monitoring of selected sites. Broad-scale surveys will often measure a number of aspects that are expected to relate to ecosystem services or processing, for example, biogenic habitat diversity, sediment characteristics (e.g. grain size, organic content and contaminants), bird numbers and macrofaunal and macroalgal community composition. Estuarine fish are much less likely to be surveyed, due to their mobility and the expense associated with collection. Time-series monitoring is likely to be very specific and select a single aspect of the system that can be simply linked to service delivery. Regional councils are also increasingly looking to increase the cost-effectiveness of their assessment by linking their broad-scale survey to their time-series information. The broad-scale information provides a larger-scale context, and sometimes more holistic view, while the time series provides information on natural variability in condition versus that which may be a response to anthropogenic pressures.

Aspects of the estuarine ecosystem such as intertidal vegetated habitats could be easily used to reflect carbon storage or shoreline stability services, with the assumption that large changes to ecosystem services will also affect the measured aspect. As regional council monitoring programmes increasingly use intertidal macrofauna as indicators, the use of biological trait analysis will allow this type of data to be linked to ecosystem service delivery. In both of these cases, easily quantified measures of ecosystem health are used as surrogates for service delivery, and there is a need for research to test the efficacy of these measures (Barbier et al. 2011). There is also a need to complement the biophysical assessment with social studies of the current values and perceptions of service delivery from estuaries and these will need to take into account changes in values associated with social and economic factors versus changes in knowledge and appreciation of service delivery.

Is there evidence that the capacity of ecosystems to provide services is reaching critical levels?

While attempts to assess ecosystem condition are becoming more common, the degree of information on which to base such assessments is highly variable around the country. In many estuaries, even basic monitoring and resource inventory are absent. Even where information is being collected, analysis usually focuses on trends in the abundance of species or changes in habitat types or area. Many of the changes in the services our estuaries provide have undoubtedly occurred undocumented. This makes defining baselines against which to develop evidence-based policy and management difficult.

As discussed above, in New Zealand estuaries, sediment entering from the land is a major stressor. Increased sedimentation rates have been documented, with concomitant changes to tidal flows, the ratio of sand to mud flats and the disappearance of widespread cockle beds (along with other native suspension-feeding shellfish), loss of seagrass and expansion of mangroves. While the disappearance of suspension-feeders would affect benthic–pelagic coupling and the ability of the estuaries to act as a filter, in many estuaries large beds of the Pacific oyster have invaded, possibly supplying the same service (albeit now focused primarily in the upper portions of the estuary).

Mangroves have also extended, affecting many of the services directly valued by people (visual aesthetics, walking, swimming, and boating) and services generally by displacement of other habitats and species with different processes. Fragmentation of biogenic habitats has also been implicated in decreased ability of these habitats to provide biodiversity (de Juan and Hewitt 2011).

But are we approaching critical levels for our ecosystem services? Our use of estuarine ecosystems is growing, with increasing urbanisation in some areas and more intensive farming, on land and in the water, in others. Climate change effects are also going to challenge the integrity of estuarine ecosystems. However, defining the adaptive capacity of estuarine ecosystems is difficult. Sometimes ecosystem change and the corresponding decline in ecosystem services are gradual and occur over long time frames. Such chronic loss of ecosystem services certainly affects human well-being but over decadal or intergenerational time frames. In this case, whether we are approaching critical levels is a value judgement. Given the range of values held within our society for our estuarine and harbour ecosystems it is impossible to gain consensus. Unfortunately, perspectives on values, states and trends are easily biased by shifting baselines that plague ecological comparisons when information on ecosystem history is limited (Dayton et al. 1998; Duarte et al. 2009).

However, some ecosystem changes are non-linear or abrupt and sometimes irreversible. These ecosystem shifts are currently impossible to predict (de Young et al. 2008), but the implications are clear: homogenisation of communities and ecosystems due to reductions in foodweb complexity, decreased diversity within functional groups and biogenic habitat structure, as well as decreases in the size of organisms. There are many specific reasons for these abrupt changes, but four general categories can be identified. First, the magnitude and nature of the stress causing change is beyond the ability of the ecosystem to adapt to within the timescales of impact. Second, multiple stressors that interact in synergistic ways have been identified from the way contaminants and sediment type affect species distributions (Anderson 2008; Thrush et al. 2008b). Third, intrinsic features of the ecology of certain ecosystems, that is, ecological thresholds, exist. Ecological processes that involve feedbacks or indirect relationships between biota and their environment are likely to be predisposed to threshold effects. In such systems, chronic and cumulative impacts on the organisms involved in feedback processes have the potential to fundamentally shift ecosystem process without extreme forcing when the feedback is broken. The potential for such a change to occur as a result of changes in sediment type or nutrient concentrations affecting densities of large bioturbating organisms has been demonstrated for New Zealand estuaries (Thrush et al. 2012). Finally, there are events that occur outside our management options, which may interact with other stressors. The risk of these is often underestimated when we are considering management options, yet they can occur regularly. A 36% reduction in cockle abundance occurred in Whangateau Harbour between 2004 and 2010. The El Nino-Southern Oscillation (ENSO) regularly changes the temperature and nutrient conditions in north-eastern New Zealand and was a major player in the sudden death of these cockles. The Christchurch earthquake had dramatic effects on the Avon-Heathcote Estuary, although probably not to the extent of the 1932 Napier earthquake on the Ahuriri Estuary. One of the few documented regime shifts in a New Zealand estuary occurred when an ENSO event coincided with a management change (reduced nutrient input) and the natural recruitment cycle of the dominant habitat-structuring organism in Manukau Harbour (Hewitt and Thrush 2010). A tubeworm mat that had been stabilising large patches of intertidal sand banks disappeared and a new, more depauperate community based on deposit feeders resulted.

Perhaps posing questions like 'are we approaching critical levels for our ecosystem services?' will not take us in the most sustainable direction. Thinking about ecosystem dynamics and responses to cumulative and multiple stressors highlights the difficulties of defining management limits to extraction or stressor loading. We desperately need more creative thinking focused on maintaining the resilience of our estuaries and the development of techniques to trade off uses in these multi-use and multi-value ecosystems. Recognising the true value of ecosystem services will be important in such processes.

ASSESSING THE VALUE OF ECOSYSTEM SERVICES FOR HUMAN WELL-BEING

Estuarine ecosystem services provide a range of benefits that can be valued in a variety of ways associated with consumptive use (e.g. harvesting), direct (e.g. recreation), indirect non-consumptive use (pollution control) and non-use values (preservation). In most cases there are no markets for these services, making monetary valuation difficult and indirect (Turner et al. 2010; Luisetti et al. 2011). Nevertheless, there are an increasing number of studies starting to consider the monetary value of estuarine and marine products and services; however, they usually consider easy-to-quantify goods such as the value of fish, aquaculture, changes in land and housing values, and the benefits of ports. Even such restricted analyses to date have indicated significant economic value, for example the estuaries of the Waikato Region were valued at NZ$863 million per year (Statistics New Zealand 2003). Often valuation exercises are not conducted at the estuarine scale, for example, tourism contributes to the economy with combined domestic and international expenditure of NZ$23.4 billion and a direct contribution to the GDP of NZ$6.2 billion. While not all of this can be attributed to estuarine and maritime pursuits, there is no doubting that they play a significant role.

A potential method for assessing the value of other ecosystem services lies in identifying the potential to recoup restoration costs. Recent analysis of the economic benefits (in terms of generating underpinning ecosystem services) of restoring oyster reefs in estuaries of the USA has highlighted the benefits of restoration and conservation (Grabowski et al. 2012). While other methods are available to economically value the more difficult underpinning services (Spangenberg and Settele 2010), these have yet to be employed in a New Zealand estuarine context. This is not surprising because the critical first step of defining services and providing a stocktake has yet to be performed. Putting a price on nature always requires a careful consideration of the feedbacks within and between the ecological, social and economic systems associated with estuaries. As we have stressed, estuarine ecosystems are likely to exhibit a number of important ecological thresholds in response to perturbation and this risk must be fully captured if cost–benefit analysis is to capture the value of estuarine services. Ecological value depends on quantity of intact system processes, not on their scarcity (Limburg 1999).

BIODIVERSITY, ECOSYSTEM SERVICES, AND HUMAN WELL-BEING: CHALLENGES AND OPPORTUNITIES

Despite the long history of use and impacts derived from both land and sea, our estuarine ecosystems still exhibit high biodiversity values and remain critical to our tourism industry and our sense of national identity. We are just beginning to recognise fully the societal benefits and values supported by estuaries in New Zealand. Ecosystem service thinking offers tremendous opportunities for underpinning and advancing environmental policy and management, recognising the true value of nature and improving cost–benefit and economic analysis. All of these applications need to be underpinned by improving our understanding of, and the interactions between, ecosystems and social processes. From an ecological perspective there is much to learn about the interrelationships between ecosystem processes and the delivery of services. We need to strive to understand the assimilative capacity of estuaries to ensure that service delivery will not catastrophically fail. There is a lack of good monitoring data from estuaries around New Zealand that allow for trends in biodiversity to be related to both changes in environmental drivers and ecosystem performance. Similarly, we have limited data on the distribution of habitats and the connections between them that underpin service delivery. Techniques have been developed to overcome this limitation to allow spatial planning to advance in the absence of detailed habitat and community descriptions; nevertheless, the challenge will remain in the detail (Townsend et al. 2011). Ecologically meaningful data is critical if we are to manage our use of estuarine resources and address the challenge of cumulative impacts in these especially-multi-use ecosystems. It is equally important to improve our understanding of the relationships between societal values, including investment decisions, and services. We need to understand how trade-offs in use can be made and identify important cultural and ecological bottom lines, especially in multi-use ecosystems where conflicts are likely. Placing monetary values on estuarine ecosystem services is especially challenging for the underpinning regulation and maintenance services and as yet there is no national or regional stocktake of these services. Nevertheless, our current knowledge allows ecosystem services to be used to help communicate the benefits of maintaining ecosystem resilience. In these transitional ecosystems, which integrate from the land to the sea, management frameworks need to transcend many geographical and governance boundaries as well as locations ascribed to particular uses. This can be addressed by an ecosystem-based approach to management, which recognises the importance of connections between social and ecological systems that operate on different space and time scales. Shifting our thinking from simple issues-based command-and-control processes to more adaptive and inclusive management approaches is a challenge we need to consider if we are to continue to extract multiple benefits from estuarine ecosystems in our changing world.

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