Available online at www.sciencedirect.com

ScienceDirect

Estuarine, Coastal and Shelf Science 74 (2007) 349–366

ESTUARINE COASTAL AND SHELF SCIENCE

www.elsevier.com/locate/ecss

Estuarine, coastal and marine ecosystem restoration: Confusing management and science – A revision of concepts

Michael Elliott [a,*], Daryl Burdon [a], Krystal L. Hemingway [a], Sabine E. Apitz [b]

[a] Institute of Estuarine and Coastal Studies, University of Hull, Hull HU6 7RX, UK
[b] SEA Environmental Decisions, Ltd., 1 South Cottages, The Ford, Little Hadham, Hertfordshire SG11 2AT, UK

Received 18 April 2006; accepted 18 May 2007
Available online 12 July 2007

Abstract

This review presents recent concepts, understanding and experience of the restoration, recovery and human-mediated modification of estuarine, coastal and marine ecosystems. It shows that these can be divided into four categories: natural recovery from a natural or anthropogenic change (whether adverse or otherwise); anthropogenic interventions in response to a degraded or anthropogenically changed environment; anthropogenic responses to a single stressor; and habitat enhancement or creation. A conceptual framework for restoration and recovery of marine marginal and semi-enclosed areas is presented after exploring and refining the plethora of terms used in restoration science and management. Examples of management action are given including managed realignment and the restoration of docks, biogenic reefs, saltmarsh, seagrass, beaches and upper estuarine water quality. We emphasise that although recovery techniques are worthwhile if they can be carried out, they rarely (if ever) fully replace lost habitat. Moreover, while they may have some success in marginal or semi-enclosed areas such as coastal bays, estuaries and fringing habitats, they are less relevant to open coastal and marine habitats. Therefore the best option available in the latter can only be to remove the stressor, as the cause of any change, to prevent other stressors from operating and to allow the conditions suitable for natural recovery. This review emphasises that whereas some ecological concepts related to restoration are well understood, for example, the nature of ecosystem structure and functioning, others such as carrying capacity, resilience and ecosystem goods and services are still poorly quantified for the marine and estuarine environments. The linking between these ecological concepts and the management framework is also relatively recent but is required to give a holistic approach to understanding, managing and manipulating these environments.

Keywords: estuaries; coasts; recovery; rehabilitation; restoration; remediation; carrying capacity; resilience

1. Introduction to recovery terminology and concepts

There is an increasing need to remedy long-standing adverse effects of human activities on estuarine, coastal and marine ecosystems. This constitutes the *Response* part of the DPSIR framework in which *Drivers* (human demands on the systems) and *Pressures* (the precise activities leading to change) result in *State Changes* (in the natural features) and *Impacts* on the socio-economic uses of the systems; the latter in turn require a *Response* in order to reduce, mitigate and/or compensate any adverse effects (McLusky and Elliott, 2004). While there is an extensive body of literature, terminology and experience relating to terrestrial and freshwater systems (e.g. Perrow and Davy, 2002a,b), it is only recently that such experience has been gained for the coastal and estuarine systems (e.g. Fonseca et al., 2002; French, 2006; Simenstad et al., 2006) and little is available for open marine systems (see Perrow and Davy, 2002a; Livingston, 2006). Furthermore, given the difficulties of determining the level of change in open marine areas and the scale of the change, very little practical restoration has been carried out for open marine systems (Hawkins et al., 1999, 2002).

Bradshaw (2002) emphasises the terms restoration, rehabilitation, remediation and reclamation from a terrestrial viewpoint

* Corresponding author.
E-mail address: mike.elliott@hull.ac.uk (M. Elliott).

0272-7714/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2007.05.034

and so it is necessary to translate these terms to the estuarine, coastal and marine environments. In particular this includes the recovery or re-attainment, by natural active or passive means, of the physical, chemical and biological environments. However, although some aspects are well understood for the marine and estuarine environments, such as sediment–hydrography relationships and poor sediment quality following pollution, other aspects such as the effects of species re-introductions and the determination of viable population sizes are more difficult in open, dynamic marine systems (cf. terrestrial and freshwater areas).

The need for habitat restoration in coastal areas, especially those subjected to intensive agriculture, urbanisation and tourism, has increased because of a large historical loss and alteration of habitats and therefore adverse ecological impacts (Madgwick and Jones, 2002) (Table 1). Because of this, there are now many schemes which purport to be restoration, especially in North America, Europe and Australia where there is both the legislation which requires it and financial ability to carry it out (Ruiz-Jaen and Aide, 2005; French, 2006). The large number of schemes and studies, however, has led to a detailed but sometimes confusing semantics of restoration with an inconsistent, conflicting and sometimes overlapping application and interpretation of the terms ('corroborating the jargon' according to Simenstad et al., 2006), hence this review aims to present and clarify the relevant terms and approaches and then give examples from the marine, coastal and estuarine environments. In addition, the further understanding of these terms, approaches and their application requires many fundamental questions to be answered (Table 1).

The term *recovery* implies that a system will return to a previous condition after being in a degraded or disrupted one, which is often interpreted as being in poor ecological health. This condition can be evaluated and communicated in different terms, depending upon the questions being asked; studies can examine fundamental ecological processes; they can seek to examine community function, possibly in response to human activities; or they can seek to inform questions on how various ecosystem services are affected by human and ecosystem interactions. These different approaches are not mutually exclusive – data collected in support of one objective should be applicable elsewhere as long as common language and a conceptual framework linking the various levels of information have been developed. In every case, however, the return to the original state will be with (active recovery) or without (passive recovery) human intervention, analogous to medical treatment (Hawkins et al., 1999). The recovery may occur naturally but of course may be speeded-up with intervention implying that recovery will occur in the system once the stressor is removed; it can be encouraged by management actions or is the response to management actions. If recovery is truly successful then the community established will be similar in species composition, population density and size and biomass structure to that previously present or present at a comparable (unimpacted, unaffected) site (e.g. Emu Ltd., 2004). The ecosystem goods and services provided and its carrying capacity will have been recovered or been regained to the pre-impact state. Despite this, it is questioned whether the original state can ever be achieved even if it is known (Simenstad et al., 2006); it is more likely that the recovery will be evaluated using single or sets of structural, functional or socio-economic indicators of recovery, which may or may not return to pre-impact states, whether known or not.

Ecological recovery of a disturbed habitat depends upon several biological factors, such as the sources and transport of propagules, which may require management to effect or enhance the natural processes (Pratt, 1994). Similarly, long-lived and poorly dispersing target species may need particular management through re-introduction (Associated British Ports Research and Consultancy Ltd., 1998). As such, newly restored wetlands may have to be inoculated with biota from similar aquatic ecosystems to ensure effective colonisation (Pratt, 1994), unless the created site is adjacent to established sites and where opportunity exists for exchange and transport of natural propagules (Associated British Ports Research and Consultancy Ltd., 1998). Recovery can be accelerated through management actions, for example, the use of appropriate oil

Table 1
Conditions driving the need for restoration, and the questions that must be considered to identify the type of restoration necessary or possible (modified and expanded from Madgwick and Jones, 2002)

Restoration is driven by the need to overcome:	Questions which help define restoration approach:
○ reductions in habitat and species diversity, and habitat size and heterogeneity; ○ reductions in the population size, dynamics and range of many species; ○ fragmentation of habitats increasing the vulnerability of remaining isolated pockets to natural or human-induced environmental changes, especially if fragmentation prevents the movement of propagules; and ○ reductions in the ability of naturally functioning ecosystems to provide economically important goods and services such as erosion protection, nutrient reduction, or carbon retention	What is expected of a natural habitat; and what are the natural ecosystem goods and services, can these be quantified and thus replaced? What the human uses are for the system and the demands on the system, and are these compatible with natural ecological structure and functioning? Can the stressors be stopped, mitigated or compensated; and if so will the system recover on its own or require some degree of intervention? Is the system to be restored to a pristine state or merely fit-for-purpose? Are there some human impacts which are unavoidable? What are the human impacts against a background of natural and wider change, such as global climate change?

spill clean-up techniques but, similarly, it can be hindered by inappropriate action such as the wrong type of clean up (Hawkins et al., 1999).

2. Passive recovery

Recovery will occur in ecosystems once stressors have been removed but this depends on properties allowing them to either absorb change or attain an improved structure and functioning. These properties include *recoverability*, *resilience* and *adaptation* but also *carrying capacity* as an indication of the overall desired state of the system.

2.1. Recoverability

Recoverability can be defined as '*the ability of a habitat, community or individual (or individual colony) of species to redress damage sustained as a result of an external factor*' (MarLIN Glossary, 2005). It is an inherent property of the ecosystem in that certain ecosystems may have a greater potential for recovering from stress than others; for example, a mobile subtidal sandbank whose physical and biological structures created by a high-energy regime will have greater recoverability than more stable areas to anthropogenic causes of change such as beam-trawling or aggregate extraction (Collie et al., 2000). However, such communities may be less resilient to disturbance by other stressors such as organic enrichment; hence recoverability depends on the stressor, the impacted species/community and the temporal and spatial intensities of the stressor.

2.2. Ecosystem or ecological resilience/robustness

Ecosystem resistance and resilience have been defined in conflicting ways. Resilience is most simply defined as 'the ability of an ecosystem to return to its original state after being disturbed' (MarLIN Glossary, 2005) or 'how fast the variables return to equilibrium following perturbation' (Pimm, 1984); though this may also be termed 'robustness' (Loreau et al., 2002). Ecosystems may be regarded as being in stability states (Bengtsson et al., 2002) such that ecological resilience is the amount of disturbance that an ecosystem in one stability state can absorb before it is changed to another state, although this is also at times termed 'resistance'. Tett et al. (2007) define resilience as the ability of the ecosystem to recover from disturbance, and state that an ecosystem shows resistance by initially reacting little to increases in pressure. Costanza et al. (1992) defines resistance similarly, albeit from another viewpoint, as 'the degree to which a variable is changed following a perturbation.' Holling (1986), on the other hand, calls this same property resilience, defined as 'a system's ability to maintain structure and patterns of behaviour in the face of disturbance.' Peterson (2000) defines ecological resilience to be 'the amount of change or disruption that will cause an ecosystem to switch from being maintained by one set of mutually reinforcing processes and structures to an alternative set of processes and structures'.

Taking these definitions together, resistance and resilience, by their various definitions, are inherent properties of the ecosystem which indicates its ability to absorb change against a background of the complexity and/or variability of the ecosystem. This feature can also be interpreted as redundancy in the system, for example, if the system is sufficiently complex it is unlikely that the loss of one or two species will cause a change in the system from having one set of characteristics, such as feeding (trophic) structure, to another. The latter, regarded as a cascade effect (Kaiser et al., 2005), may occur under large-scale stressors such as fishing selectively removing one group (e.g. demersal fish such as cod) to the benefit of another (e.g. pelagic species). Furthermore, the structure and complexity of food webs centre on connectance (the number of links between species) and the length of food chains, amongst others (Dunne et al., 2004). These properties of food webs change with scale, diversity and complexity, and this is particularly the case with estuarine, coastal and marine food webs which have large numbers of opportunist and generalist feeders (Elliott and Hemingway, 2002). In particular, highly connected communities tend to be more robust (resilient) to species loss than low connected communities and so perhaps estuarine and marine communities have a greater structural robustness than other ecosystems (Dunne et al., 2004). Ecosystem resilience can thus be exceeded when environmental and/or human-mediated stressors synergistically change the state (Dunne et al., 2004). As such, Gunderson (2000) considers resilience as the time that a system takes to return to the stable state following a natural/human perturbation but also uses the term 'adaptive capacity' as the processes that modify ecological resilience. Hence, while resilience may be measured as time it depends on the amount of inherent complexity/variability of an ecosystem.

As an inherent, fundamental property, all ecosystems are resilient but to differing degrees and a more specialised and less variable ecosystem may have a lower resilience than a naturally highly variable one. For example, a highly variable ecosystem such as an estuary is more likely to be able to withstand and/or absorb anthropogenic stress than a less variable one (Elliott and Quintino, 2007). Similarly, the amount of resilience a system possesses relates to the degree of disturbance required to fundamentally disrupt the system causing a large-scale change to another state controlled by a different set of processes (Gunderson, 2000; Bengtsson et al., 2002). In turn, reduced resilience increases the vulnerability of a system to smaller disturbances that could previously have been absorbed. However, even in the absence of disturbance, gradually changing conditions (e.g. nutrient loading, climate change and habitat fragmentation) may exceed threshold levels, resulting in an abrupt system response (e.g. The Resilience Alliance, 2002; Kaiser et al., 2005). Because of these aspects, it is suggested here that resilience and recoverability are synonymous so only the former is required.

The paths of decline and recovery of systems are regarded as trajectories or performance curves (Simenstad et al., 2006) which although conceptually valid have not been defined quantitatively. Any attempt at restoration thus requires either an active or passive approach in which the habitat is made, respectively, to re-trace or re-traces without intervention the trajectory of decline. Aronson and Le Floc'h (1996) refer to three different options for recovery: *restoration* by reactivating (or allowing to be reactivated) natural processes including species re-introductions; *rehabilitation*, a short-term management measure to attain a specific ecosystem attribute, goods or service; and *reallocation* where over the long-term new trajectories produce new ecosystems and uses.

The conceptual model of Tett et al. (2007) takes this further to suggest that resistance to change is the amount of (anthropogenic) stress (pressure) that a system can accommodate before it deteriorates. Following the removal of the stress, the system will recover although not necessarily along the same trajectory of decline, the difference being termed hysteresis which differs with types of system and stressor. They then implied that more stress was needed to be removed to make the system recover, a feature they called resilience. Given the above discussion, we have revised their conceptual model to indicate that systems do not necessarily recover their former state and also that their ability to recover is termed resilience (Fig. 1). For a given structural or functional parameter (which only defines one aspect of the multidimensional definition of ecosystem health, status and function), resistance can be defined as the amount of a given pressure that can be applied without a deterioration in status (as defined by a specific measure). As a pressure is removed, Type I Hysteresis represents the lag in recovery; status may not improve for some time after the pressure is removed. Given time, though, status may recover, although it may not return to original levels. Resilience can thus be defined as the degree of recovery, based upon a given measure, compared to the original status – complete resilience results in a return to the original level, partial resilience is a return to some lower (or higher) level, with Type II Hysteresis being the difference between the two. Whilst the definition of resilience in Fig. 1 differs from those above, our review of the ecological science and management literature reveals that the terms resistance and resilience are used differently (and sometimes interchangeably). Thus, we conclude that Fig. 1 should be followed and that consistence and clarity of use within an application are possible (and required) although this use is likely to conflict with use elsewhere in the literature. Because ecosystem status is defined by a multidimensional set of variables, an understanding of the interplay is required between various ecosystem parameters to an overall definition and management of ecosystem "health", status, function, and services. Then, if restoration, remediation or recovery does not result in a return to reference conditions, ecosystems can be evaluated over space or time in terms of their functional characteristics, or their ability to provide valued ecosystem services. Within such a conceptual framework, habitat degradation, management and recovery can be addressed using a variety of indicators. Despite this, empirical evidence for this model is still required for the marine environment in order to determine the precise patterns, sequence, magnitude and repercussions of these changes.

The fact that these subtly different and often interchangeable uses of the terms resistance and resilience are seen throughout the literature suggests that they should be used with care, and always with a clear statement of their meaning in the given context.

2.3. Adaptation

Adaptation can generally be defined as the ability to alter something for a new use but ecologically it refers to the processes or coping strategies to be used by communities to increase their resilience (or decrease their vulnerability) to ecosystem changes. For example, reducing freshwater flow into an estuary will reduce the brackish (euryhaline) component of the fauna and increase the marine (stenohaline) component. While individual species may not adapt to the

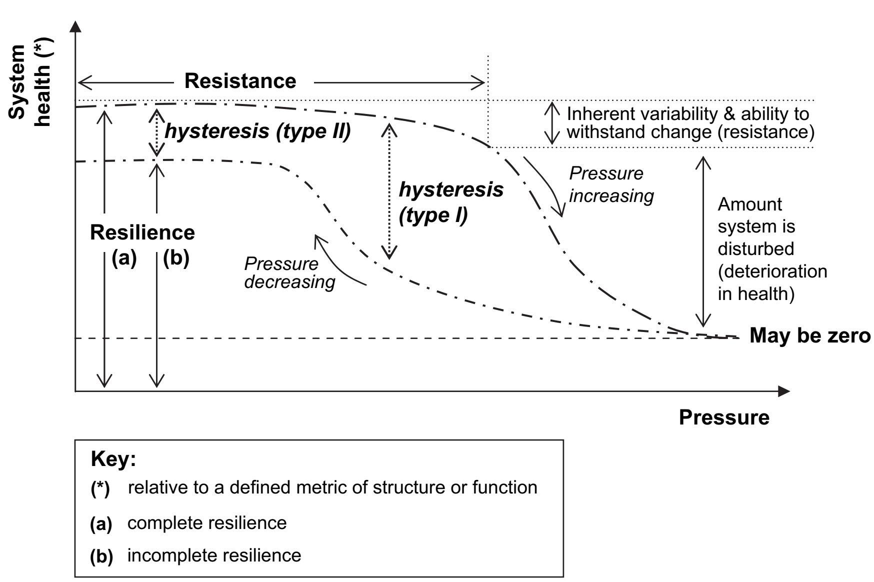

Fig. 1. A conceptual model of changes to the state of a system with increasing pressure (revised from Tett et al., 2007).

changed salinities, the new community adapted to the new situation may function in the same way as the original one. Thus, for example, an increased estuarine salinity will change a community from being dominated by the euryhaline ragworm, *Hediste diversicolor*, to one dominated by the more marine catworm, *Nephtys hombergi*, but the system still maintains its functioning (Dr D.S. McLusky, University of Stirling, Scotland, pers. obs.). Similarly, a community may be regarded as having adapted to changing conditions if, through temperature regime change due to climate change, warmer water species migrate into an area and colder ones migrate out of it (see Laffoley et al., 2005). This, however, changes the focus of the definition of recovery to a stressor from that of a given population (structure) to that of ecosystem function, as is reflected in the discussion of Fig. 1. Whilst the community above will be considered to be adapting successfully within an ecological context, regulatory contexts that focus primarily on structural indicators may not deal effectively with such adaptations.

2.4. Carrying/assimilative capacity

Simenstad et al. (2006) rightly ask the question 'what are we restoring to?' – most simply we consider the aim is to reinstate the loss through environmental damage of ecosystem goods and services which equates to a loss of carrying capacity; however, the latter needs further defining and quantifying in relation to habitat loss and gain. Carrying capacity was formerly and more usually used as an ecological concept but more appropriately it is considered here in terms of both environmental and societal demands, i.e. what the natural system wants and can accommodate and what are society's aspirations (Cohen, 1997; Yozzo et al., 2000; Elliott and Cutts, 2004; MacLeod and Cooper, 2005; Van Cleve et al., 2006). Baretta-Bekker et al. (1998) define it as '*the maximum population size .... possible in an ecosystem, beyond which the density cannot increase because of environmental resistance*'. Similarly, the European Environment Information and Observation Network (EIONET) defines ecological carrying capacity as (1) the maximum number of species an area can support during the harshest part of the year, or the maximum biomass that it can support indefinitely, (2) the maximum number of grazing animals an area can support without deterioration (http://www.eionet.eu.int/gemet/concept).

Carrying capacity has been further defined ecologically by Cohen (1997) as 'the number of individuals in a population that the resource of a habitat can support', 'the point at which the recruitment equals mortality', 'the average size of a population that is neither increasing nor decreasing' or, as related to limiting conditions 'under steady state conditions, the population .... is constrained by whatever resource is in the shortest supply'. In relation to commercial stocks, Cohen (1997) gives five further definitions: population size at which the standing stock of animals is maximal, population size at which the steady yield of animals is maximal, animal population size being at that for maximal plants, the size of a harvested population that belongs to a sole owner, and the population size of an open access resource. MacLeod and Cooper (2005) suggest that it is exceeded when population mortality exceeds recruitment because of environmental limitations (a stressor that a particular ecosystem can withstand before the ecological value is unacceptably affected) – a definition more widely adopted in fisheries science. However, they also acknowledge the difficulty of defining ecological value and unacceptable change – again implying a value judgement regarding what is acceptable change against a reference condition (see below).

The above definitions tend to be based around commercial populations so are not fully relevant to habitat restoration and therefore for natural systems we take carrying capacity as '*the maximal population (and/or community) that can be supported by the area's resources, principally space, food and reproductive partners*'. Relating this to temperate estuarine intertidal areas, a high carrying capacity can be their ability to support high numbers of over-wintering wading birds and/or juvenile fish. Hence, until recently, estuarine ecological carrying capacity related to resources (principally food and space) available for use, a concept used more for wading birds than other organisms (see, e.g. Stillman et al., 2005). Measures of both habitat quality and resource quantity are therefore needed to determine the population supported by an area although, in the particular case of over-wintering bird populations, factors at their polar breeding sites away from temperate coasts will also have an influence. Where a resource such as food or space is limiting, it can be assumed that carrying capacity for birds is reached when one bird has to leave a site after the arrival of another (Dr J. Goss-Custard, Centre for Ecology and Hydrology, UK, pers. comm.). However, the development of competitive interference between birds has indicated that food resource competition alone cannot be used for determining carrying capacity as it underestimates the demands for space by birds (Stillman et al., 2005). This feature has recently been determined for the schemes designed to compensate for the loss of wetlands caused by the construction of the Cardiff Bay Barrage (Dr J. Goss-Custard, Centre for Ecology and Hydrology, UK, pers. comm.).

Although the above indicates the ecological nature of carrying capacity, here we also recommend including societal aspects such as the ability of an area to support a given human activity. For example, a well-mixed, high-energy area may have a high carrying capacity to absorb organic wastes without adverse effects being detected. This can also be described as the system's *assimilative capacity*, a term often used to indicate the ability of an area to accommodate (as in disperse, degrade and assimilate) polluting discharges without damage (McLusky and Elliott, 2004). MacLeod and Cooper (2005) further consider carrying capacity to have a range of definitions: *physical carrying capacity* refers to space limitations, i.e. the number of activities an area can withstand before there is some change to quality, for example, number of berths in a marina. *Social carrying capacity* refers to the human population densities an area can sustain before numbers start to decline because of actual or perceptions of amenity decline, such as coastal tourism. *Economic carrying capacity* refers to the extent to which an area can become changed before the economic goods and services are adversely affected, for example, excessive coastal development for tourism which reduces the desirability of the area.

Therefore we recommend a composite definition that carrying capacity is the maximum number of users (population and community) that can be supported by the ecological or economic goods and services provided by an area. The aim of successful restoration therefore is to regain, maximise or enhance the carrying capacity.

3. Active recovery

While natural recovery will take place sooner or later as long as a stressor is removed, human-mediated actions are often used to enhance recovery, hence the term here active recovery. This has been classified here into actions combating a degraded environment and the effects of a single stressor.

3.1. The human-mediated response to a degraded environment

3.1.1. Rehabilitation and restoration

Rehabilitation can be defined as "*the act of partially or, more rarely, fully replacing structural or functional characteristics of an ecosystem that have been reduced or lost*". It may also be the substitution of alternative qualities or characteristics than those originally present with the proviso that they have more social, economic or ecological value than existed in the disturbed or degraded state (Edwards, 1998). Thus the rehabilitated state is not expected to be the same as the original state or as healthy but merely an improvement on the degraded state (Bradshaw, 2002). This is brought about by management actions but requires a (possibly cultural) decision regarding the preferred final state. For example, a low organic state of an intertidal area from which a sewage discharge has been removed is likely to be socially preferable even though it supports fewer wading birds.

At its simplest, ecosystem restoration has been defined by Baird (2005) as '*activities designed to restore an ecosystem to an improved condition, however the latter is defined*'. However, this does not imply the highest quality of the final ecosystem but merely that it is better than the degraded situation. Because of this, a preferable definition of restoration is '*the process of re-establishing, following degradation by human activities, a sustainable habitat or ecosystem with a natural (healthy) structure and functioning*' (created from Bradshaw, 2002 and Livingston, 2006). Simenstad et al. (2006) take this to be returning an ecosystem to its pre-disturbance condition and functioning and Bradshaw (2002) suggests that although the non-ecological uses of the term imply a return to an original state which is perfect and healthy, an ecologically preferable definition is '*the process of assisting the recovery and management of ecological integrity. Ecological integrity includes a critical range of variability in biodiversity, ecological processes and structures, regional and historical context, and sustainable cultural practices*' (from the Society for Ecological Restoration, 1996, in Bradshaw, 2002). Thus, restoration implies an active intervention but not necessarily to an original, pristine state (cf. recovery which is regarded as a return to an original state) (Hawkins et al., 1999). The term *active restoration* has been used by authors (e.g. Hawkins et al., 2002) but it is suggested here that this is a tautology as, using the available definitions, there cannot be passive restoration (which we argue should be termed recovery). Restoration can accelerate recovery although this could lead to an alternative state. Also the original state may not be known (Simenstad et al., 2006) and so the desired state will be a best guess, subjective or valued judgement (Van Cleve et al., 2006).

Fonseca et al. (2002) make the further distinction between compensatory restoration and primary restoration. The former '*refers to any action taken to compensate for interim losses of natural resources and services that occur from the point of injury until the recovery of those resources/services to baseline. Conversely, primary restoration refers to actions that return the injured natural resources and services to baseline.*' *As we cannot determine a reliable baseline nor have we accepted criteria to measure it then classification into compensatory and primary restoration is an unnecessary complication for the wider marine environment and is not required further. Similarly, the approach of Aronson and Le Floc'h (1996) to distinguish long-term restoration and reallocation from short-term rehabilitation and rejuvenation also adds unnecessary complication and is not used further.*

Habitat restoration (also termed re-creation) may simply be a means of alleviating losses caused by environmentally damaging human activity (Doody, 2003) and Lewis (1990) pragmatically suggests that it is not necessary to know the original condition of the natural habitat but only to know what habitat type was there (e.g. saltmarsh), and to return it to the same general habitat type. Hence although an older reference, Zedler (1984) considers that restoration requires a return to the exact pre-existing condition, it is suggested here that this is rarely achieved, particularly as the original state may be unknown. As a further complication, restoration is against a background of natural long-term change or short-term variability in habitats, a particular feature of estuaries. A habitat may be restored in the short term (such as to remove the effects of a temporary polluting discharge), or long term (such as returning land claimed decades if not centuries previously to saltmarsh) (Elliott and Cutts, 2004).

Management and restoration can only be gauged as effective if a required end-point is pre-defined (see also Van Cleve et al., 2006), such as identifying and giving protection to conservation value. Such management may include: allowing areas to vary naturally without intervention or intervening to maintain the status by preventing change which may be counter to the designated conservation interest or objective (Doody, 2003). As such, coastal habitat restoration may simply involve the reversal of trends, such as agricultural intensification, or abandoning a cultivated area (French, 2006). Degraded or damaged habitats, however, may require further intervention to change the site, such as flooding of agricultural land to restore mudflats and/or saltmarsh, or restoring sediment supply (Doody, 2003; French, 2006).

Most coastal, estuarine and marine restoration, as an active, human-mediated process, has been small-scale although there is the potential for larger scale schemes (e.g. Perrow and Davy, 2002a,b). On a small scale, keystone species and ecological engineers (structural species) play a central role in effecting restoration (Fonseca et al., 2002; Hawkins, 2004). For example, seaweed restoration has been achieved by active means but this has usually been for commercial reasons such as increased harvesting or to allow recovery in areas following seaweed and faunal collection. Similarly, although seagrass beds can be restored after only a partial removal or the effect of disease, seeding and planting produce limited success with human-mediated losses outweighing the restoration gains. Despite this, as long as the water column and sediment conditions are suitable then recovery will follow; for example, a suitable nutrient regime, water transparency, inundation period and substratum type for attachment will allow recolonisation of seagrasses as long as their propagules are available (Fonseca et al., 2002). These examples show that while small-scale ecosystems, such as seagrass beds, saltmarshes, biogenic reefs and beaches, have been successfully restored, large-scale ones have not, for example, the Canadian Grand Banks affected by overfishing (Hall, 1999).

3.1.2. Remediation and re-creation

Remediation can be defined as '*to rectify, to make good*' (Bradshaw, 2002), or '*action taken at a site following anthropogenic disturbance to restore or enhance its ecological value*' (Emu Ltd., 2004), hence emphasising the action or process rather than the end-point reached (Bradshaw, 2002). It can encompass a range of approaches to restore or enhance a site's ecological value, from non-intervention through to habitat enhancement or creation. It is reiterated, however, that complete restoration of a habitat is rarely achieved. Re-creation, in contrast, implies the creation for a second time of a system or habitat in order to increase the carrying capacity and the ecological goods and services of the overall system. For example, a saltmarsh may be re-created once a dyke has been removed and the saline intrusion regained (French, 2006).

As indicated above, the terms restoration, rehabilitation, remediation and re-creation have been used interchangeably. To all intents and purposes for estuaries and coasts, they appear synonymous and so, although terrestrial biologists may disagree (e.g. Bradshaw, 2002), it is proposed that only the term restoration is used for estuaries and coasts.

3.1.3. Re-introduction, re-establishment, reclamation and replacement

While the above aspects all refer to habitats, these terms indicate, respectively, the first and subsequent stages in the replacement of an ecosystem's structural component, usually a species and especially a structuring species, in sufficient quantities to allow it to regain its overall nature and thus restore the ecological functioning. A species may be brought (reintroduced) into an area from where it disappeared and then its population becomes re-established (and hopefully sustainable and self-maintaining). Examples of this include the transplanting of seagrass stands, reed beds, corals and other biogenic reefs such as mussel beds. While this may allow the re-creation of the habitat visually and will encourage the maintenance of associated species, it should be used with caution because of the potential for a change in genetic diversity when organisms are transplanted or when propagules are brought from elsewhere (Hawkins et al., 1999). Furthermore, while terrestrial and freshwater species have been reintroduced, this has been less tried in estuarine and marine areas.

Reclamation also appears to be more suited to terrestrial areas and activities than aquatic ones in that it may be defined as 'making land fit for cultivation' or 'to bring back to a proper state' (Bradshaw, 2002). This does not necessarily imply a return to an original state but merely making an area fit for purpose. Similarly, *replacement* is more similar to creation and may be implied if the new area has a use or character different from the original or degraded (Bradshaw, 2002) without judging whether the new state is better than the previous one. To replace could also be used for the substitution of a habitat, for example, introducing artificial reefs on seabed which previously was bare subtidal sediment; however, this has also been termed habitat enhancement (see below). Bradshaw (2002), for terrestrial examples, considers the term *replacement* of the original by something different and that replacement and rehabilitation are encompassed by *reclamation*.

It is recommended that the terms re-introduction and re-establishment are only used in relation to species and that the terms reclamation and replacement should not be used for marine and coastal areas, especially while the term reclamation is still (erroneously) used as an original synonym for the term land-claim, hence an original loss of habitat.

3.2. The response to a single stressor

3.2.1. Mitigation and compensation

On land, in freshwaters and in estuaries, an increasing number of planning decisions require compensatory, mitigation or restoration measures to minimise the effects of developments. The open marine environment is likely to follow this trend and so there will be an increasing number of such measures although it is unlikely that these will include the land-based measures such as habitat and species translocation, especially for ecosystem engineers, captive breeding programmes, restoration of degraded habitats, post-development restoration works or habitat creation (Madgwick and Jones, 2002).

Mitigation, '*the act of making any impact less severe*', usually relates to a potential plan or project (Elliott and Cutts, 2004) and is often a condition of any licence, authorisation, permit or consent for any activity to occur following an Environmental Impact Assessment (EIA) (Morris and Therivel, 2001; Wood, 2003; Glasson et al., 2005). It must be very well defined as site-specific, to occur within a site and to relate to a particular activity carried out in a particular manner at a specified place. For example, dredged material disposal will be licensed and thus managed through mitigation to minimise any negative impact on the receiving ecosystem; this includes the choice of the receiving area (e.g. disposing of dredged fine sediment resulting from harbour clearance into a fine sedimentary area) (e.g. McLusky and Elliott, 2004). In some cases, however, it is the consequence of a stressor rather than its cause which is managed, for example, external forces such as climate change leading to sea-level rise. The management action to that stressor, such as beach nourishment or managed realignment, is not addressing the cause of the change but merely is responding to the consequences.

We agree with Bradshaw (2002) that mitigation is not directly connected to restoration although he suggests that it can be an outcome of restoration (or rehabilitation or reclamation) and may involve the improvement of another ecosystem. As indicated below, however, we emphasise that this is more correctly compensation than mitigation.

Although the term mitigation is widely used, it is emphasised here that certain effects cannot be mitigated, for example, the loss of intertidal mudflats taken for industry or port expansion. In this case, mitigation can only be outside the site where the natural asset is compensated by creating a habitat elsewhere (Elliott and Cutts, 2004) as *compensation* is regarded as '*to make up or make amends for damage*'. *In an ecological context, we conclude that there are three types of compensation: (1) economic compensation for a loss of ecosystem goods and services (e.g. pay the fisherman, landowner), (2) resource compensation (e.g. improve the ecosystem goods and services such as enhance a fishery) and (3) ecological compensation (re-creation of ecosystem goods and services, i.e. 'creative-conservation' such as wetland creation)* (Elliott and Cutts, 2004).

Where habitat loss is unavoidable, compensation is an accepted requirement within EIA. Under existing legislation, this aims at ensuring the survival of the range and variation of habitats and distribution of species in the face of increasing stressors. As such, re-creation or creation of habitat would occur together with site protection measures (Doody, 2003). Ideally, the new habitat should be as close as possible to the area it replaces, although compensating habitat loss is rarely successful in replacing habitats with similar ones (Doody, 2003). In addition, practical considerations such as the availability of compensatory land without excessive costs will dictate where compensation schemes can occur. Habitat creation often then involves an unavoidable and pragmatic compromise between new and existing habitats (Associated British Ports Research and Consultancy Ltd., 1998). For example, whilst developing a compensatory site may ensure the maintenance of the overall population of wading birds in an area, it cannot be assumed that this aids the survival of those individuals which formerly fed on the destroyed area (Associated British Ports Research and Consultancy Ltd., 1998). On the Humber Estuary, eastern England, an outer estuary saltmarsh site has been created as compensation for the loss of a mid-estuary intertidal mudflat area, therefore not replacing like-with-like but perhaps creating a lesser impact on the overall ecological goods and services of the estuary than would have been the case without compensation. Furthermore, Bradshaw (1987, 2002), primarily discussing terrestrial systems, suggests that mitigation implies the rehabilitation of another system – as indicated here, we emphasise that this is more correctly termed compensation (i.e. *ex situ* creation of habitats) as opposed merely to mitigation as the lessening of an effect *in situ*. *Taking all of these features, it is recommended here that the term mitigation should only be used for in situ actions and elsewhere it should be compensation*.

3.2.2. Habitat enhancement and creation

The term enhancement has been used to imply the establishment of an alternative ecosystem although the term in general means *to raise in degree*, *heighten*, *intensify*, *or to increase the value*, *importance or attractiveness* (Bradshaw, 2002). Ecologically, habitat enhancement can simply be defined as a management approach which directly or indirectly increases the ecological value, goods and services of the habitat, for example, increased numbers of over-wintering wading birds on an estuary as shown by measures to increase the carrying capacity of the Menai Strait, North Wales, to support wading birds (oystercatcher) in conflict with mussel fisheries (Caldow et al., 2004). Bradshaw (2002) suggests that enhancement is the action of improving a habitat which already has a good ecological functioning hence giving the term a qualitative, human-perception aspect. For example, Emu Ltd. (2004) suggested that placing an artificial reef is habitat enhancement but it is argued here that this implies a quality judgement by presuming that a three-dimensional reef structure is preferable to the two-dimensional seabed previously in the area. Hence, in this case it is preferable to talk of habitat creation.

Marine habitat creation is an anthropogenic intervention which produces a habitat not previously there (cf. habitat re-creation), for example, where terrestrial area is converted into a wetland habitat; some authors give this a fixed time dimension such as where the created habitat has not been there within recent history (e.g. a century) (Lewis, 1990; Associated British Ports Research and Consultancy Ltd., 1998; French, 2006). This action presupposes that, given the historical loss of coastal and estuarine habitats, then any new habitats are regarded as environmentally beneficial (Livingston, 2006). Placing a different habitat within an area should be regarded as creation rather than re-creation. For example, artificial reefs placed on an otherwise sandy seabed should be regarded as creating new habitat and increasing the biodiversity of an area rather than replacing lost habitat. Hence, because the gain of one habitat (e.g. wetland or artificial reef) implies the loss of another (e.g. terrestrial or sandy seabed), it is questionable whether this is enhancement of the overall system.

Wetland/intertidal habitat creation is difficult in many coastal and estuarine sites which have fixed upper or lateral boundaries; these may be natural boundaries such as where intertidal areas abut a sea cliff, or artificial ones in the case of groynes, sea-walls or other infrastructure. Without intervention, such as realignment of those boundaries, an overall loss of intertidal habitat and thus conservation interest will occur due to relative sea-level rise (through global change and isostatic rebound and termed 'coastal-squeeze'), or where storm frequency and intensity are increased (McLusky and Elliott, 2004). Managed realignment may similarly involve the replacement of one habitat by another, but replacing habitats that were lost on a like-for-like basis is difficult given the site-specific nature of marine and estuarine areas. There are benefits, however, in creating new replacement habitats outside existing site boundaries (Doody, 2003) thus increasing ecological goods and services.

Taking the above comments, we recommend that producing new habitat can be termed creation or enhancement whereas re-creating habitat that was present within historical records, no matter how old, should be termed restoration.

4. The current understanding and concepts of recovery

The term recovery is used here to collectively describe all cases of improvement to ecosystem goods and services supported, thus it includes restoration, adaptation, re-creation, remediation, enhancement, etc. As shown above, the extensive semantics of ecosystem recovery has led to confusion (cf. Hawkins et al., 1999; Bradshaw, 2002; Simenstad et al., 2006) and so, following the recommendations above, we are in a position to harmonise the use of those terms; Table 2 illustrates the plethora, linking and use of the terms used in restoration science and management and thus the potential for confusion. Because of this, we partly agree with Bradshaw (2002) for the use of restoration as a single term which covers not just putting back what was there prior to the introduction of the stressors or degrading force, but also as a blanket term for *all activities which seek to upgrade and improve a damaged area*, *to recreate what had been destroyed*, *recover its use and restore its biological potential*. Bradshaw's (loc. cit) use of the term restoration, however, does not cover all management actions such as habitat creation, mitigation and compensation; terms which are increasingly being tested legally (see also Perrow and Davy, 2002a,b). It is recommended that the terms which have been struck-through in Table 2 should not be in use in the present context.

The review here suggests that the natural and human-mediated recovery and/or improvement of marine and estuarine habitats and ecosystems can be divided into four categories:

1. natural recovery from a natural or anthropogenic change (whether adverse or otherwise);
2. anthropogenic interventions in response to a degraded or anthropogenically changed environment;
3. anthropogenic responses to a single stressor; and
4. habitat enhancement or creation.

The first of these implies a passive, ongoing process which depends on a habitat's potential for recovery (this is synonymous with the terms non-intervention/natural recolonisation used by Emu Ltd. (2004) for aggregate extraction areas). The second and third categories imply management actions which may occur at the site which is degraded (*in situ* management actions) or at a site elsewhere (*ex situ* management actions) (Table 2). The second class also includes the term given by Emu Ltd. (2004) of Active–Passive Intervention (such as natural recovery following the implementation of an administrative restriction, e.g. Marine Protected Areas and No-Take Zones); however, such a contradiction as Passive Intervention is not helpful in the present discussion and so is not used further here. The second category also includes the term restoration such as the result of Managed Realignment leading to wetland re-creation, albeit possibly after a long time since the wetland was first lost (poldered). The final category includes both an improvement of a habitat and the creation of a habitat (e.g. artificial reefs) in areas not previously

Table 2
Recommendations for the terminology and framework for natural and anthropogenic recovery of ecosystems and habitats. It is recommended that the terms which have been struck-through should not be in use in the present context

(Passive) attributes of an ecosystem/habitat		(Active) intervention by a management response (*1 *in situ*; *2 *ex situ*; *3 not necessarily *in situ*) to a:		
		Degraded environment	Single stressor	
Term	Explanation	Action	Action	Effect
Recovering	What is occurring in the system	~~Re-creation (*1)~~	Habitat enhancement (*1)	Increase ecosystem goods and services
~~Recoverability~~	~~Inherent property of the system~~	Restoration (*1)	Mitigation (*1) (NB only for *in situ*)	Minimise effects
Adapting	What is occurring in the system	~~Remediation (*1)~~	Compensation (*2) (NB only for *ex situ*)	Replace a loss of ecosystem goods and services
Adaptability	Inherent property of the system	~~Rehabilitation (*1)~~	Habitat creation (*3)	Replace lost ecosystem goods or services or produce new ecosystem goods and services
Resilience	Inherent property of the system	Re-establishment (*1) (NB only use for species)		
Carrying capacity	Inherent property of the system (desired state) both for ecology and socio-economy	Re-introduction (*1) (NB only use for species) ~~Reclamation (*1)~~ Replacement (*1) ~~Active restoration (*1)~~ ~~Compensatory and primary restoration (*1)~~		

having that type of habitat. However, this implies a quality judgement (which itself implies subjectivity and operator bias) that the science and engineering are sufficient to improve habitats and also that one type of habitat is preferable to another, for example, an artificial reef providing greater hard substrata is preferable to the sandy substratum on which it is placed.

The four categories here were determined independently but reflect the three basic approaches to restoration – passive, active and creation – concluded by the detailed review of Simenstad et al. (2006) based primarily on North American experience. The separation in the present analysis of these into four reflects the need to classify the available active responses to different types of stressor. Despite this, both reviews conclude the need to encourage ecological structural and functional recovery.

The refinement of terms (Table 2) has been used here to produce a conceptual model which links the changes in ecosystem structure and functioning as the result of human impacts to management measures and which attempts to clarify the terms and concepts used in ecological restoration and recovery (Fig. 2). Degradation implies a reduction and deterioration in both ecosystem structure and functioning although Bradshaw (2002) suggests that this will not necessarily occur equally in both of those ecosystem attributes. As it is difficult

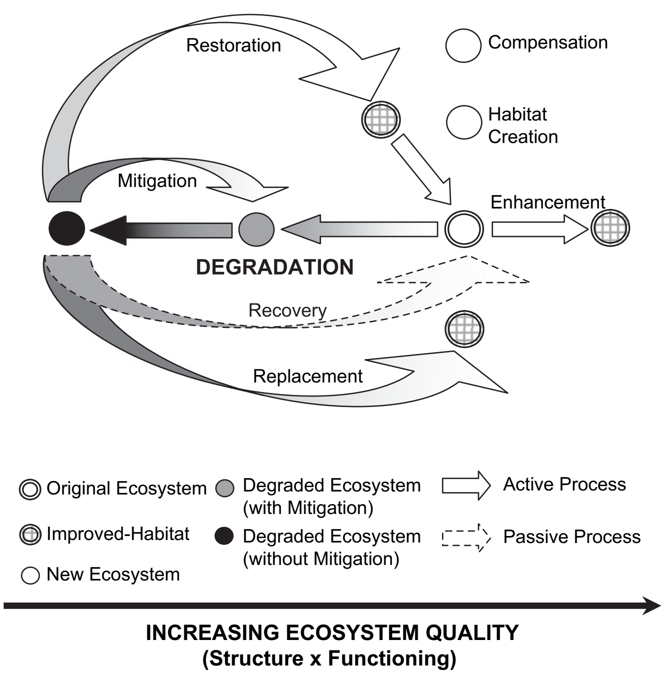

Fig. 2. A conceptual model illustrating the nature of natural recovery of a degraded ecosystem and the terms used in human-mediated (active) restoration. The model indicates that habitats can be produced (◙) which are an improvement on the degraded state but not necessarily to the original state (◎), whereas other ecosystems (○) are newly created systems. The recovery (light grey dashed arrow) can be to the original state or some distance along that pathway of regaining ecosystem quality. The model emphasises the movement of ecosystems along a continuum (horizontal axis) of ecosystem quality, which combines both structure and functioning, whereas the position of ecosystems in the vertical axis in the model has no meaning.

in many environments, especially the marine environment, to quantify simultaneous changes in structure and functioning as co-ordinates in a bivariate model (as used in Bradshaw, 2002), the conceptual model here merely has a single (horizontal) axis for increasing ecosystem quality which encompasses both attributes.

Ecosystem and habitat restoration science and management are essentially the manipulation and re-establishment of the physical and chemical environments, the manipulation of the biota and the monitoring and appraisal of restored systems and the restoration process (Perrow and Davy, 2002a). Manipulation and monitoring are anthropogenic responses to environmental stressors but may require a long-term approach to determine the required outcomes (Simenstad et al., 2006). The stressors causing the habitat or ecosystem to degrade can occur at a particular site and by a well-defined stressor (e.g. dredging), outside the site but also by a well-defined stressor (e.g. dredged material disposal), or outwith the area and by large external forces such as global climate change (an 'exogenic unmanaged pressure'). In the latter, the management actions within a small area cannot address the causes of the change and so can only use adaptational strategies to address the consequences.

The causes of the degradation of the marine, coastal and estuarine systems can be summarised as the introduction into or removal from an area of physical and chemical materials, physical structures and organisms (McLusky and Elliott, 2004). Restoration/recovery should therefore be aimed at reversing such adverse effects and as such, De Jonge and De Jong (2002) indicate, albeit with a Dutch perspective, five main themes of estuarine and coastal restoration:

- counteracting abrupt transitions between marine and freshwater due to flood prevention works and changes to water management;
- counteracting previous restrictions on physical processes, for example, the stabilisation of dunes, construction of barriers and dredging of navigation channels;
- providing compensation mechanisms aimed at replacing areas, species, and habitats lost by previous actions;
- reducing temporarily occurring water quality problems such as noxious blooms, low dissolved oxygen areas, and algal mats; and
- providing compensation for events outside the system, for example, the responses such as managed realignment required to counter sea-level rise or isostatic rebound.

These features are illustrated below using examples of management action to restore or recreate particular habitats.

5. Examples of management action

5.1. Managed realignment

Managed realignment (also known as setback, managed retreat or de-polderisation) is a recent and increasingly important soft-engineering management option where wetlands are created either as water storage areas to combat flooding, or as flood defence areas to combat sea-level rise, erosion and/or isostatic rebound (land sinking) and the resultant habitat loss (Edwards and Winn, 2006; French, 2006). These schemes are created by moving back dykes (sea-walls) and allowing flooding between the new and old sea-walls. This gives benefits, in order, for human safety, then economics and lastly the ecological system and is thus considered a '*win-win-win*' situation (Yozzo et al., 2000; Elliott and Cutts, 2004). They are also used as compensation schemes to offset the loss of habitat from port developments, e.g. Welwick on Humber Estuary, eastern England (Edwards and Winn, 2006; French, 2006; Associated British Ports Marine Environmental Research, Southampton, pers. comm.). The environmental gain may be as habitat re-creation, for example, if agricultural land formerly claimed from wetlands is returned to wetland, or as the prevention of further loss, as in a port expansion compensation scheme.

5.2. Dock restoration

A well-documented example of habitat creation and restoration but also one which well illustrates the potential for confusion in the semantics of ecological restoration is provided by management improvements to disused docks (e.g. Hawkins et al., 1999, 2002 and references therein). This has been referred to variously as dock restoration, redevelopment and habitat re-creation. Essentially, however, it is improving an artificial structure in order to make it an artificial lagoon after the recovery of water quality and the mixing regime. This leads to a new colonisation by hard substratum fauna and flora which will be very different from that soft-substratum biota historically in the area prior to the dock being created. Thus the new system is an improvement (in cultural terms) on the degraded dock but is not the creation or even re-creation of a natural system.

Despite this, dock restoration does indicate the role of structuring species such as suspension feeding mussels in habitat re-creation. The management strategy described by Hawkins et al. (2002), faced with eutrophic conditions, aimed to provide hard substratum to support filter feeders which then had the capacity to change the system's turbidity and thus address the consequences of high nutrients. This occurred together with a control on the causes of the high nutrients, i.e. the diffuse and point source inputs. These management actions show the importance of understanding multiple states shown by an ecosystem and the movement between those, e.g. in the case of the dock system from a turbid, eutrophic state to clear, oligotrophic waters and the role of bioengineers in that process. In this case, the movement from the former to latter states by introducing filter feeders and reducing nutrient inputs showed the importance of understanding feedback mechanisms.

5.3. Saltmarsh restoration

Saltmarsh restoration has a long history in North America (e.g. Simenstad et al., 2006) and Europe but here the Wadden Sea (Germany, the Netherlands, and Denmark) will be used as an example because of its long history of being poldered leading to the loss of wetlands. The Guiding Principle of the Trilateral Wadden Sea Policy is '*to achieve, as far as possible, a natural and sustainable ecosystem in which natural processes proceed in an undisturbed way*' (Dr H. Marencic, Wadden Sea Secretariat, pers. comm.). The policy is linked to a Principle of Restoration which states that '*where possible, parts of the Wadden Sea can be restored if it can be demonstrated by reference studies that the actual situation is not optimal, and that the original state is likely to be re-established*' (Madgwick and Jones, 2002). The lost saltmarshes are to be restored through a programme of opening summer dykes to increase natural morphology, changing drainage patterns and improving vegetation structure and functioning. This will then improve the carrying capacity of the system for wading birds.

Based on past experience, saltmarsh restoration also indicates the importance of scale, for example, the restoration of a corridor through a saltmarsh disturbed by pipe laying is of a different order to restoring saltmarsh after coastal realignment (Hawkins, 2004). While the former involves minor change to an area and the recolonisation from adjacent areas, whole marsh restoration requires the creation of all suitable features such as physiography and topography, sedimentation and the inflow of seeds (Simenstad et al., 2006). Zedler and Adam (2002) emphasise the creation of the physical structure, salinity, water flow, sediment supply, etc. and the need to overcome the problems of fragmentation as prerequisites to successful restoration. Perhaps more than other examples, saltmarsh restoration emphasises the linking of the engineering and ecological aspects, with both *effective science* and the *effective use of science* (Van Cleve et al., 2006) and the role of bioengineering in overcoming land-claim, impounding, subsidence, draining, erosion, etc.

Saltmarsh restoration by increasing their area and quality also has the advantage of a large case-history which has produced a set of pragmatic recommendations aimed at:

- encouraging warping (accretion) to increase tidal height and allow saltmarsh plants to develop;
- increasing inundation to impounded marshes by breaching, opening sluices and increasing channel and culvert size;
- excavating to historical lowered elevations and lowering the topography to aid water retention;
- planting of *Spartina* together with the beneficial use of dredged material to stabilise shorelines;
- freshwater run-off regulation or diversion to control and/or increase salinity;
- removing, neutralising or sequestering contaminants in sediments; and
- control or prevention of inflow by invasive species (adapted from Zedler and Adam, 2002).

5.4. Seagrass restoration

Seagrass restoration shows the importance of knowing the links between an ecological structuring element and the creation of a suitable physical environment for it to colonise and develop. The US NOAA uses Habitat Equivalency Analysis (HEA) to indicate what is needed to regain a habitat and what measures are required to show that it has been regained. This produces metrics or indices of what is required to regain the appropriate ecological goods and services, for example, seagrass shoot density, as well as the criteria for selecting a compensatory site away from the original injury site:

- it is at depths similar to nearby seagrass beds;
- it was anthropogenically disturbed;
- it exists in areas that are not subjected to chronic storm damage;
- it is not undergoing rapid and extensive recolonisation by seagrasses;
- seagrass recolonisation has been successful at similar sites;
- the area is sufficient to conduct the project; and
- the restored and lost areas are similar quality habitat (Fonseca et al., 2002).

5.5. Beach restoration

Coastal beach restoration worldwide is performed to enhance ecological aspects, especially for high profile species such as nesting turtles and birds, or for socio-economic reasons such as the replenishment, re-creation (or even creation) or reinstatement of beaches for tourism. There are examples of restoration and re-creation of habitats in which the primary aim is for coastal defence and thus public safety rather than an increased ecosystem functioning, although this is also achieved (Walmsley, 2002). Beach nourishment or recharge using natural or dredged material (termed beneficial use) is widely used, for example, on soft coasts and in estuaries around the North Sea to counter erosion and movement of sediment, and to compensate for changes due to sea-level rise and isostatic adjustment by re-creating or extending mudflats. This type of restoration extends only to creating the appropriate physical conditions of tidal height, inundation period, topography and particle sediment structure and then allowing the biota to recover unaided (e.g. E. Mitchell, IECS, University of Hull, UK, pers. comm.). Although there is some recovery by fauna buried within the recharge (as long as the accretion is not too deep), the main recolonisation is by adult fauna laterally from established areas and also by settling juvenile recruits. More data are required, however, on the effects of different recharge methods (e.g. pumped and trickle recharge) and of the length of time required for an area to regain its full range of ecological goods and services and, in particular, to regain its functioning in terms of supporting bird and fish predator populations.

A further example is shown by the beaches of North-east England which were severely degraded by the long-term dumping of colliery waste and, in tandem, the beaches were subsiding due to the extraction of the sub-surface coal (Dr L. Humphries, University of Sunderland, UK, pers. comm.). Although their topography and tidal profile were maintained, as the net result of input and subsidence, the beaches were of low biological value. Following cessation of dumping and extraction, the beaches have been allowed to recover without intervention. As this encouraged a natural infill by sand to approximate the state prior to degradation, non-intervention has prevented a more natural beach profile and hence a recovery of their fauna.

5.6. Upper estuarine water quality

While many of the above examples relate to remedying the permanent or long-term loss of habitats by physiographic changes, in many industrialised area the temporary loss of habitat is of greater ecological consequence. Many estuaries are naturally hypernutrified and organically enriched such that with additional organic matter inputs (e.g. from sewage discharges), the upper estuarine turbidity maximum area becomes a water quality barrier (McLusky and Elliott, 2004). The low dissolved oxygen levels in these regions prevent, on some seasonal and tidal conditions, migration by diadromous fishes and occupation by estuarine resident fishes (Elliott and Hemingway, 2002). For example, the Forth, Clyde, Mersey, Scheldt, Delaware and Thames estuaries have all experienced these water quality problems and the resultant effects usually with a reduced species number and, in some cases, e.g. the Thames Estuary, a loss of the fish community. Remedial measures involving the reduction in sewage discharges and, in the case of the Thames Estuary, artificial oxygen introduction (using the 'Thames bubbler') during certain conditions have produced recovery of the fish communities. These actions have also been accompanied by re-stocking with salmonids to increase the population viability.

6. Frameworks for management action to achieve restoration

As shown here, semi-enclosed, coastal and fringing systems and estuaries have an increasing case-history of restoration, partly because they also have the most severe impacts (McLusky and Elliott, 2004). Enclosed waters such as estuaries, bays and lagoons are amenable to restoration through water quality improvement and their physical environment can also be manipulated such as by increasing flushing (e.g. Hawkins et al., 1999, 2002) or changing boundaries. In contrast, in an open marine system, there is a limited opportunity for restoration and so the best approach to habitat recovery is to do nothing – to stop the cause of the impact and allow recovery through time (Hawkins et al., 1999). The exception to this is where structural species and ecosystem engineers are reintroduced/restored/re-established, e.g. kelps, corals, biogenic reefs, in order to allow the recovery of the remainder of the system (Hawkins et al., 1999). Evidence is given, for example, by Clark (2002) in which the field survey and experimental experience from coral restoration in tropical areas can be used for other biogenic reefs in temperate areas, e.g. mussel beds. She also shows the value of artificial structures in creating the physical support into which biota can colonise.

The inherent resilience of the marine environment has shown rapid recovery to some acute stressors, for example, following oil spillage and tanker accidents. Rocky shores, especially in high-energy rocky areas, have recovered rapidly such that their basic ecological functioning has returned within an annual cycle. Elsewhere, succession patterns may then take some time to stabilise (e.g. for the *MV Amoco Cadiz* tanker accident in Brittany in 1978 the impact lasted as long as that shown by a severe winter; Glémarec and Hussenot, 1982). In contrast, inappropriate clean-up measures such as the use of detergents or even hot, freshwater on rocky shores will not only not aid recovery, it may even create a larger effect. Hence, Hawkins et al. (2002) and Hawkins (2004) concluded that after major oil spills there is no need to attempt active restoration of rocky shores.

In offshore areas, there is a limited ability for restorative action other than to stop the activity; for example, reversing adverse impacts of overfishing by prevention such as introducing No-Take Zones (e.g. scallop dredging off the Isle of Man). In other areas, a joint management of human activities creates benefits, for example, the Dutch RIKZ (National Institute of Coastal and Marine Management, Ministry of Public Works) emphasises that a coastal wind farm would also have the beneficial effect of preventing beam-trawling, considered to be a more damaging activity. It is likely that eventually the presence of offshore wind farms will also be regarded as a form of enhancing recovery and restoration of the seabed through the *de facto* creation of Marine Protected Areas and No-Take (Trawl) Zones.

The interconnected nature of open marine systems will allow rapid recolonisation following improvements to water quality and reversal of the deterioration of physical structure. Hence here we emphasise the need to focus on managing the physico-chemical environment together with preventing over-exploitation of the biota (e.g. fisheries) and habitat (e.g. aggregate extraction) which then allow natural recovery to occur (see also Hawkins et al., 2002; Edwards and Winn, 2006). Restoration can be used to speed up natural recovery although in some cases this will require suitable conditions to be put in place for the successful colonisation by the structural bioengineers and settlement of propagules allowing recruitment to the population. Fonseca et al. (2002) also emphasise the effect of the loss of structural elements such as seagrasses, and take the view that although they are easy to replant, it is more difficult to ensure that conditions are suitable for success. This is despite the wealth of experience for seagrasses.

The above experiences allow us to produce a suitable decision-making framework for marine, coastal and estuarine restoration (Table 3). The case studies show that in dynamic systems natural recovery is seen as the most appropriate and most likely mechanism to restore the ecosystem goods and services. Rehabilitation, as in dock restoration, is a pragmatic option to enable a potential return to a specific state than a complete return to a pre-impact natural condition. This approach may be necessary when the natural condition and/or baseline is not known or is highly dynamic. Where biotic resources such as seaweeds have been removed by commercial exploitation, they can be restored by a combination of allowing natural recovery after reducing/suspending the extraction, increasing or restoring the hard substrata, or removing the grazers such as sea urchins. Hence successful restoration requires good science and hypothesis testing and is a mixture of science and engineering. As emphasised by Van Cleve et al. (2006) there is the need for both effective science and the effective use of science, and by Simenstad et al. (2006) there are good pilot cases but there is the need for larger scale projects.

Any ecological-based scheme of management is likely to be accompanied by a no-net loss policy and achieving the reinstatement of ecological resources, goods and services requires full rehabilitation of a site (*in situ* restoration), alternative (*ex situ*) compensatory sites to be used, or a combination of both. However, creating compensatory sites is relatively recent in the estuarine and coastal fields and non-existent in the open marine area and hence there is a poor case-history; accordingly there may be a problem of creating a habitat in a compensation area where it did not occur before, in that conditions inherently

Table 3
Summary of decision-making for marine, coastal and estuarine restoration (modified and expanded from Hawkins et al., 1999)

Action level	(1) Stop chronic stressors from acting or remove stressors (e.g. discharges, over fishing)	
	Or: Prevent acute stressors from acting (e.g. oil spills)	
	(2) Initiate clean up (if appropriate)	
	Open marine systems	Semi-closed and marginal coastal and estuarine systems
Actions	Do nothing, allow recovery Stop unnecessary interventions and cumulative impacts Assess time-scale of recovery	Restore physical and chemical environments Restore biological and physical structural integrity Enhance and allow settlement/recruitment Consider value of transplants, bio-manipulation
Advantages	Low-cost, natural	Restoring to a defined/agreed state; working with and enhancing natural processes; being seen to be 'doing something'; and increasing case-history
Disadvantages	Slow, perception of 'doing nothing'	Often using untried technology, with a possibility of non-success; hampered by a poor understanding of succession in some areas; may lead to an unnatural or non-original state; and possibly costly

were not suitable. For example, Fonseca et al. (2002) suggest that the calculation of lost ecological goods and services requires a knowledge of (1) the area lost, (2) the time required for the lost functioning at the site and during the period of degradation to be recovered, and (3) the path of the recovery function. This may be known for seagrasses, saltmarshes and corals (Perrow and Davy, 2002a,b; Livingston, 2006; Simenstad et al., 2006) but especially lacking for other marine habitats and ecosystems.

7. Recovery options and measures of successful restoration

A selection of habitats/ecosystems – estuary, intertidal, subtidal and pelagic – can be used to illustrate recovery and restoration options (Table 4) and shows that the nature of restoration may differ with type of stressor causing change, the nature of the habitat, other uses of the area and available funds and technologies. However, the largest challenge is how to determine that restoration has been successful in ecological or societal terms or at least what is the performance, even in cost-benefit terms, of the measures taken. As shown above and elsewhere (e.g. Simenstad et al., 2006; Van Cleve et al., 2006, and references therein), the success or effectiveness of restoration is often a quality judgement, thus involving observer bias. At present, despite the lack of long-term quantitative information on restoration schemes, it is relatively easy to show that a restored site is better or more natural than previously, that it has created a greater wetland area and thus space and organic matter for the system to function. Whether, however, this gives a net increase in ecological goods and services remain to be tested.

Ruiz-Jaen and Aide (2005), in reviewing vegetation-based restoration schemes, found that most measures used to gauge success relate to diversity, vegetation structure and ecological processes. For estuarine, coastal and marine cases these translate as ecological structure and functioning and physico-chemical attributes which can then be used to determine what is needed to progress restoration science and management. In particular, we agree with Fonseca et al. (2002) that further studies are needed to:

1. derive appropriate metrics to indicate restoration success;
2. evaluate lost resources;
3. derive appropriate selection criteria for compensatory sites;
4. provide accurate project cost estimates and a true and complete cost-benefit appraisal which integrates economic and environmental costs and benefits; and
5. determine the role of disturbance as a fundamental ecological process which influences the success of restoration.

These are needed to determine in quantitative terms the trajectory of recovery, hence the need to compare with controls either in space or time, and to provide better information of the time taken to achieve a recovered, functioning ecosystem (Ruiz-Jaen and Aide, 2005; Simenstad et al., 2006). Craft et al. (2002) suggest that it takes 12–15 years to achieve similar structural attributes for a restored site in relation to a reference but of course this differs with the type of habitat and the means by which the restoration success is measured. Feest (2006) considers that biodiversity is the most important consideration to be achieved or enhanced via restoration of damaged habitats and, based on an earlier list created by the European Environment Agency, gives a set of indicators of biodiversity although most of these reflect structural rather than functioning attributes. The Society of Ecological Restoration (2004) listed nine ecosystem attributes to be achieved under successful restoration. Those lists (EEA and SER) have been combined and greatly modified here to reflect estuarine, coastal and marine situations to provide 12 objectives which can be measured and which relate to structural and functional attributes (Table 5). Many, however, are site and case-specific and also it is unlikely that there are resources to measure all at any one site. In addition, while some are relatively easy to measure, e.g. the extent of a biotope, others are more nebulous, e.g. the maintenance of ecosystem functioning.

The objectives for successful restoration (Table 5), and the indicators which must be derived to determine when those

Table 4
Potential for responses to change within example ecosystems: ✓, applicable and valuable; –, applicable but not valuable; and 0, not applicable

Recovery option	Ecosystem			
	Estuary	Intertidal	Subtidal	Pelagic
Removal/remediation of contaminated areas of disused structures	✓	✓	✓	✓
Coastal protection – soft engineering	✓	✓	–	0
Coastal protection – hard engineering	✓	✓	✓	0
Waste minimisation and waste treatment	✓	✓	✓	✓
Exclusion zones and statutory limits to physical resource utilisation	✓	✓	✓	✓
Exclusion zones and statutory limits to biological resource utilisation	✓	✓	✓	✓
Habitat restoration, restoration, creation, replacement	✓	✓	✓	0
Compensation of: (a) users (b) resource (c) habitats	✓	✓	✓	✓
Barrier removal: (a) water quality; (b) physical structures	✓	✓	–	–

Table 5
Estuarine, coastal and marine proposed objectives to indicate successful restoration

Objective	Structural (S) or functioning (F)
(1) Spatial extent of biotopes, habitats and/or ecosystems are as expected and self-sustaining under the natural physico-chemical conditions and in comparison to reference conditions	S, F
(2) Community diversity and structure, population abundance and reproduction, and species distribution are as expected under natural prevailing conditions and resilient to natural disturbances	S
(3) Threatened and/or protected species are in good status	S, F
(4) Genetic diversity of farmed and wild-caught fish and shellfish species is not compromised, i.e. socio-economic importance	S
(5) Extent of protected areas is maintained	S
(6) The area under sustainable management for aquaculture or wild fisheries is as large as possible given societal demands and ecosystem constraints	S
(7) Nutrient dynamics are as expected under the prevailing hydrographic conditions (e.g. residence time) and not greatly modified by anthropogenic activities	F
(8) Invasive, alien or introduced species are absent or in low numbers and have not affected the integrity of other species, the habitat or ecosystem	S, F
(9) Potential threats internal and external to the system have been eliminated, minimised, mitigated or compensated and there is no detectable change in biodiversity through climate change (exogenic unmanaged pressures)	S
(10) Community functioning and functional groups, e.g. as shown by marine trophic index and structure, are as expected and sustainable/stable in the long-term	F
(11) There is no physical or chemical disruption in connectivity of migration routes (i.e. no fragmentation) within and between ecosystems, e.g. water quality is protected so there is no permanent or temporary habitat loss	S, F
(12) There is the potential for the sustainable exploitation of species and or materials (e.g. marine biopharmachemicals)	S, F

objectives have been met, provide the links between many estuarine, coastal and marine management initiatives which will form the debate for the next few decades. In North America, as elsewhere, despite a history of restoring wetlands, there is still the need to collate and learn for previous studies, to set realistic goals and understand what can and cannot be achieved (Simenstad et al., 2006). In Europe, restoration has to be set within the European Marine Strategy, the proposed Marine Strategy Framework Directive (e.g. Borja, 2006) and the Habitats and Water Framework Directives (Apitz et al., 2006). The UK Government's Marine Bill (2007) incorporates Marine Spatial Planning (Elliott et al., 2006a) and marine zonation schemes to provide priorities for management (Boyes et al., 2007). The OSPARCOM (the Oslo and Paris Commission for the NE Atlantic) and HELCOM (the Helsinki Commission for the Baltic) have adopted Ecological Quality Objectives as part of the Ecosystem Approach to marine management (Elliott et al., 2006b; Rogers et al., 2007). Each of these initiatives requires developing and adopting objectives and quantitative indicators both as aims for management but also as a means of determining when management has been successful (e.g. Rogers and Greenaway, 2005; Aubry and Elliott, 2006). Hence, these initiatives reflect the objectives created here for habitat restoration (Table 5).

8. Conclusions and recommendations

The ultimate aim in restoration, to create a self-supporting and self-maintaining ecosystem which does not require further management (Ruiz-Jaen and Aide, 2005), thus requires not only scientific knowledge but also a creative aspect (Baird, 2005), indeed restoration may be as much art as science. Because of this, we need an expanded quantitative knowledge base and good case studies, perhaps even where schemes have been attempted on a 'let's try it and see what happens basis' (possibly also called *adaptive management*, see also Simenstad et al., 2006).

This review emphasises the role of invertebrates and plants in restoration (as ecosystem engineers) and the responses of fishes and higher vertebrates. It also shows, however, the need for experimental and practical approaches in the marine area, for further case studies and a continuing need for a hypothesis-driven scientific approach – the 'futuristic' approach advocated by Simenstad et al. (2006) is more simply the use of good science in decision-making. Importantly, we need to develop and test hypotheses such as the underlying model that functioning develops linearly with the development of structure and that restored sites will become functionally equivalent to reference systems (Bradshaw, 1987; Fonseca et al., 2002; Zedler and Adam, 2002).

The restoration of terrestrial and freshwater systems has a long history and experience from which the estuarine and marine systems can learn although because of a different nature of degradation and open characteristics, many of these approaches may not be successful in dynamic marine and estuarine areas. Despite this, experience allows recommendations to be made for coastal and marine habitats and ecosystem scale management and restoration (Table 6). Economic strictures require a cost-benefit assessment of restoration not least to check the contention by Holl and Cairns (2002) that the cost of restoration is at least an order of magnitude greater than the cost of prevention. Socio-economic science has to link with the natural sciences to determine the value of restoration across various scales and to allow the results of localised actions to be extrapolated to larger areas. In particular, we need to quantify the chances of success and the benefits of restoration (Table 6). The experience of restoration on sheltered and fringing habitats (saltmarshes, beaches and estuaries)

Table 6
Requirements for information in restoration science to management (modified from Hobbs, 2002 and Baird, 2005)

Question	Task		Examples
(1) Is the current environmental state within acceptable limits and, if so, can it be maintained? Do we know what the acceptable limits are? Have we got the metrics to measure them? Can maintenance be determined and if so within what time-scales?	Identify the cause of the problem, e.g. have there been changes in or to:	(a) Biotic and/or environmental structure and functioning	Assemblage types, hydrography, substratum, species loss or decline, invasion; fragmentation of habitat
		(b) Fluxes of physical, chemical and biological materials	Species movement, water and/or nutrient fluxes
		(c) The aesthetic or amenity value	Actual or perceived perception of a reduction in quality
		(d) Existing and historical management regimes	Encouragement of land-claim for agriculture or infrastructure
	Quantify spatial and temporal repercussions on biotic and environmental attributes, hence determine:	(a) Spatial influence of stressors and their consequences	Near or far-field changes and influences resulting from hydrographic (water and sediment) distortion
		(b) Temporal duration of stressors and their consequences	Short- or long-lived changes to water and sediment patterns and the resulting change to the communities
(2) Whether, and if so how and at what cost, can restoration or mitigation activities restore the system to within the range of acceptable states? Are the latter known in scientific and societal terms?	Determine realistic goals for restoration, for instance:	(a) Retention of existing biota, habitat extent, underlying structure, etc. and prevention of further loss	Ensure sufficient extent of structuring elements, e.g. seagrass beds, to maintain the higher trophic levels
		(b) Removal of the stressor, coupled with slowing or reversal of processes or practices causing degradation	Reduce polluting inputs causing temporary water quality barriers
		(c) Maintenance or improvement of the potential for biological production, carrying capacity and ecosystem goods and services	Ensure sufficient environmental quality, organic production and transfer of materials between trophic levels
		(d) Integration of approaches for the sustainable use and management of near and far fields	Ensure the use of a habitat by resident and migratory species, e.g. consider nursery and over-wintering functions by fishes and birds which may also be dependent on sites far away from the area in question
(3) If restoration is not politically or economically feasible, can the geographic extent of the degraded system be contained, reduced, or functionality improved, again within socio-economic bounds?	Develop cost-effective planning and management tools for achieving agreed goals:	(a) Determine priorities for action for different single stressor and for stressors in combination and/or with cumulative effects, in different habitat types and conditions;	Indicate the most damaging pollutants, e.g. according to their persistence, bioaccumulation, toxicity and role in environmental quality degradation, together with causes of habitat removal
		(b) Spatially and temporally defined solutions and management actions	Create estuarine, coastal and marine management plans to integrate all uses, users and stressors
		(c) Acceptance and 'ownership' of the problems and solutions by the different stakeholders	Create management plans which integrate stakeholders participating within the regional and national administrative framework
		(d) An adaptive approach with feedback into management and which allows changes to actions when necessary	Ensure that monitoring has well-defined end-points, i.e. studies show when water quality improvements sufficient for ecological functioning have been achieved

and on structural components (seagrasses and biogenic reefs) reinforces the conclusion that in the open marine area, the most appropriate management action is to allow (passive) recovery after removing the cause of the degradation.

The questions posed at the start of this review imply that restoration involves knowledge of the physical, biological and social sciences but also knowledge of cultural aspects. There is the need to convince the general public of what habitats and ecosystems are required in order to produce the desired ecosystem (both ecological and economic) goods and services. As importantly, given the aim to produce habitats and ecosystems which are deemed to be better than a degraded state, this subjective aspect indicates that there is the need to consider what final states (after restoration) are acceptable. The desired quality of an environment, however, may change with time and the 'acceptability' of an improved area may be politically motivated and based on human beliefs, values and preferences (Baird, 2005; Simenstad et al., 2006), e.g. is the creation of a saltmarsh area more desirable to society than a mudflat? Cultural perceptions may become paramount in that there may be an increasing public tolerance to a degraded environment with time in certain areas: a society used to poor environments may be more willing to tolerate a poor quality habitat.

It is emphasised here that if the suitable habitat, as the physical conditions, is maintained or created (and as long as the removal of the biological resource through fisheries is not unsustainable) then biological recovery will follow. There is also, however, the need for defining and quantifying both the carrying capacity of these dynamic areas and metrics (as indicators) of success in restoration. The few small-scale experimental and test cases already carried out need to be scaled up to give quantitative information regarding the success in creating not only ecosystem structure but also functioning. Finally, although there are some lessons to be learnt from freshwater and terrestrial studies, these cannot always easily be extrapolated to estuarine, coastal and especially open marine areas.

Acknowledgements

The authors would like to thank the following for their valuable comments: Nick Cutts (IECS, University of Hull), Professor Victor de Jonge (IECS, University of Hull), Professor Steve Hawkins (Marine Biological Association, Plymouth), Dr Keith Hiscock (Marine Biological Association, Plymouth), Professor Michel Kaiser (University of Wales, Bangor), Dr Stuart Rogers (CEFAS, Lowestoft), Professor David Paterson (University of St Andrews, Scotland) and Professor Charles ('Si') Simenstad (University of Washington, Seattle) and three anonymous referees. This work was part of a project for the Countryside Council of Wales whose staff are also thanked for their input and discussion: Drs Kirsty Dernie, John Hamer, Andrew Hill and Kirsten Ramsay. The work also contributes to the project HARBASINS of the European Regional Development Fund (ERDF) INTERREG IIIB North Sea Programme. SEA acknowledges partial support by the EU 6th Framework Programme for Global Change and Ecosystems (1.1.6.3) Project Integrating new technologies for the study of benthic ecosystem response to human activity: towards a Coastal Ocean Benthic Observatory (project #505564).

References

Associated British Ports Research and Consultancy Ltd., 1998. Review of Coastal Habitat Creation, Restoration and Recharge Schemes. ABP Research and Consultancy Ltd., Southampton. Report No. R.909. Available from: <http://www.estuary-guide.net/pdfs/habitat%20review.pdf>.

Apitz, S.E., Elliott, M., Fountain, M., Galloway, T.S., 2006. European environmental management: moving to an ecosystem approach. Integrated Environmental Assessment and Management 2, 80–85.

Aronson, J., Le Floc'h, E., 1996. Vital landscape attributes: missing tools for restoration ecology. Restoration Ecology 4, 377–387.

Aubry, A., Elliott, M., 2006. The use of environmental integrative indicators to assess seabed disturbance in estuaries and coasts: application to the Humber Estuary, UK. Marine Pollution Bulletin 53, 175–185.

Baird, R.C., 2005. On sustainability, estuaries and ecosystem restoration: the art of the practical. Restoration Ecology 13, 154–158.

Baretta-Bekker, H.J., Duursma, E.K., Kuipers, B.R. (Eds.), 1998. Encyclopedia of Marine Sciences. Springer-Verlag, Berlin, Germany, 367 pp.

Bengtsson, J., Engelhardt, K., Giller, P., Hobbie, S., Lawrence, D., Levine, J., Vila, M., Wolters, V., 2002. Slippin' and slidin' between the scales: the scaling components of biodiversity–ecosystem relations. In: Loreau, M., Naeem, S., Inchausti, P. (Eds.), Biodiversity and Ecosystem Functioning: Synthesis and Perspectives. Oxford University Press, Oxford, pp. 209–220.

Borja, A., 2006. The new European marine strategy directive: difficulties, opportunities and challenges. Marine Pollution Bulletin 52, 239–242.

Boyes, S.J., Elliott, M., Thomson, S.M., Atkins, S., Gilliland, P., 2007. A proposed multiple-use zoning scheme for the Irish Sea. An interpretation of current legislation through the use of GIS-based zoning approaches and effectiveness for the protection of nature conservation interests. Marine Policy 31, 287–298.

Bradshaw, A.D., 1987. The reclamation of derelict land and the ecology of ecosystems. In: Jordan, W.R., Gilpin, M.E., Aber, J.D. (Eds.), Restoration Ecology. Cambridge University Press, Cambridge, pp. 53–74.

Bradshaw, A.D., 2002. Introduction and philosophy. In: Perrow, M.R., Davy, A.J. (Eds.), Handbook of Ecological Restoration. Principles of Restoration, vol. 1. Cambridge University Press, Cambridge, pp. 3–9.

Caldow, R.W.G., Beadman, H.A., McGroty, S., Stillman, R.A., Goss-Custard, J.D., Durell, S.E.A. le V. dit., West, A.D., Kaiser, M.J., Mould, K., Wilson, A., 2004. A behaviour based modelling approach to reducing shorebird–shellfish conflicts. Ecological Applications 14, 1411–1427.

Clark, S., 2002. Coral reefs. In: Perrow, M.R., Davy, A.J. (Eds.), Handbook of Ecological Restoration. Restoration in Practice, vol. 2. Cambridge University Press, Cambridge, pp. 171–196.

Cohen, J.E., 1997. Population, economics, environment and culture: an introduction to human carrying capacity. Journal of Applied Ecology 34, 1325–1333.

Collie, J.S., Hall, S.J., Kaiser, M.J., Poiner, I.R., 2000. A quantitative analysis of fishing impacts on shelf-sea benthos. Journal of Animal Ecology 69, 785–798.

Costanza, R., Norton, B., et al. (Eds.), 1992. Ecosystem Health: New Goals for Environmental Management. Island Press, Washington D.C., 279 pp.

Craft, C., Broome, S., Campbell, C., 2002. Fifteen years of vegetation and soil development after brackish-marsh creation. Restoration Ecology 10, 248–258.

De Jonge, V.N., De Jong, D.J., 2002. Ecological restoration in coastal areas in the Netherlands: concepts, dilemas and some examples. Hydrobiologia 478, 7–28.

Doody, P., 2003. Coastal Habitat Restoration: Towards Good Practice. Introductory Unpublished Report Produced as Part of the LIFE Funded 'Living with the sea project' (Contract No. FST20-48-006 01/0384). Available from: <http://www.english-nature.org.uk/livingwiththesea/project_details/good_practice_guide/HabitatCRR/ENRestore/AccompanyingReport.pdf>.

Dunne, J.A., Williams, R.J., Martinez, N.D., 2004. Network structure and robustness of marine food webs. Marine Ecology Progress Series 273, 291–302.

Edwards, A., 1998. Rehabilitation of coastal ecosystems. Marine Pollution Bulletin 37, 371–372.

Edwards, A.M.C., Winn, P.S.J., 2006. The Humber Estuary: strategic planning of flood defences and habitats. Marine Pollution Bulletin 53, 165–174.

Elliott, M., Cutts, N., 2004. Marine habitats: loss and gain, mitigation and compensation. Marine Pollution Bulletin 49, 671–674.

Elliott, M., Hemingway, K.L. (Eds.), 2002. Fishes in Estuaries. Blackwell Publishing, Oxford, 636 pp.

Elliott, M., Quintino, V., 2007. The estuarine quality paradox, environmental homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas. Marine Pollution Bulletin 54, 640–645.

Elliott, M., Boyes, S.J., Burdon, D., 2006a. Integrated marine management and administration for an island state – the case for a new marine agency for the UK. Marine Pollution Bulletin 52, 469–474.

Elliott, M., Burdon, D., Hemingway, K.L., 2006b. Marine ecosystem structure, functioning, health and management and potential approaches to marine ecosystem recovery: a synthesis of current understanding. Unpublished report: YBB092-F-2006 for the Countryside Council of Wales by the Institute of Estuarine and Coastal Studies. University of Hull, UK, 102 pp.

Emu Ltd., 2004. Marine Aggregate Restoration and Enhancement: Strategic Policy Overview. Report No. 04/J/01/06/0548/0437. Emu Ltd. on behalf of The British Marine Aggregate Producers Association, the Crown Estate and English Nature.

Feest, A., 2006. Establishing baseline indices for the quality of biodiversity of restored habitats using a standardized sampling process. Restoration Ecology 14, 112–122.

Fonseca, M.S., Judson Kenworthy, W., Julius, B.E., Shutler, S., Fluke, S., 2002. Seagrasses. In: Perrow, M.R., Davy, A.J. (Eds.), Handbook of Ecological Restoration. Restoration in Practice, vol. 2. Cambridge University Press, Cambridge, pp. 149–170.

French, P.W., 2006. Managed realignment – the developing story of a comparatively new approach to soft engineering. Estuarine, Coastal and Shelf Science 67, 409–423.

Glasson, J., Therivel, R., Chadwick, A., 2005. Introduction to Environmental Impact Assessment: Principles, and Procedures, Process, Practice and Prospects (The Natural and Built Environment Series), third ed. Routledge, London, 512 pp.

Glémarec, M., Hussenot, E., 1982. A three-year ecological survey in Benoit and Wrac'h Abers following the Amoco Cadiz oil spill. Netherlands Journal of Sea Research 16, 483–490.

Gunderson, L.H., 2000. Ecological resilience – in theory and application. Annual Review of Ecology and Systematics 31, 425–439.

Hall, S.J., 1999. The Effects of Fishing on Marine Ecosystems and Communities. Blackwell Science, Oxford, 274 pp.

Hawkins, S.J., 2004. Scaling up: the role of species and habitat patches in functioning of coastal ecosystems. Aquatic Conservation: Marine Freshwater Ecosystems 14, 217–219.

Hawkins, S.J., Allen, J.R., Fielding, N.J., Wilkinson, S.B., Wallace, I.D., 1999. Liverpool Bay and the estuaries: human impact, recent recovery and restoration. In: Greenwood, E.F. (Ed.), Ecology and Landscape Development: A History of the Mersey Basin. Conference Proceedings, pp. 155–165.

Hawkins, S.J., Allen, J.R., Ross, P.M., Genner, M.J., 2002. Marine and coastal ecosystems. In: Perrow, M.R., Davy, A.J. (Eds.), Handbook of Ecological Restoration. Restoration in Practice, vol. 2. Cambridge University Press, Cambridge, pp. 121–148.

Hobbs, R.J., 2002. The ecological context: a landscape perspective. In: Perrow, M.R., Davy, A.J. (Eds.), Handbook of Ecological Restoration. Principles of Restoration, vol. 1. Cambridge University Press, Cambridge, pp. 24–46.

Holl, K.D., Cairns Jr., J., 2002. Monitoring and appraisal. In: Perrow, M.R., Davy, A.J. (Eds.), Handbook of Ecological Restoration. Principles of Restoration, vol. 1. Cambridge University Press, Cambridge, pp. 411–432.

Holling, C.S., 1986. The resilience of terrestrial ecosystems: local surprise and global change. In: Clark, W.C., Munn, R.E. (Eds.), Sustainable Development of the Biosphere. Cambridge University Press, Cambridge, pp. 292–317.

Kaiser, M.J., et al., 2005. Marine Ecology: Processes, Symptoms and Impacts. Oxford University Press, Oxford, 557 pp.

Laffoley, D.d'A., Baxter, J., O'Sullivan, G., Greenaway, B., Colley, M., Nayor, L., Hamer, J., 2005. The MarClim Project: Key Messages for Decision Makers and Policy Advisors, and Recommendations for Future Administrative Arrangements and Management Measures. English Nature Research Report No. 671. Natural England, Peterborough, 42 pp.

Lewis, R.R., 1990. Marine and estuarine provinces (Florida). In: Kasler, J.A., Kentula, M.E. (Eds.), Wetland Creation and Restoration: The Status of the Science. Island Press, Washington D.C., pp. 73–101.

Livingston, R.J., 2006. Restoration of Aquatic Ecosystems. Taylor and Francis, Boca Raton, Florida, 423 pp.

Loreau, M., Naeem, S., Inchausti, P. (Eds.), 2002. Biodiversity and Ecosystem Functioning: Synthesis and Perspectives. Oxford University Press, Oxford, 294 pp.

MacLeod, M., Cooper, J.A.G., 2005. Carrying capacity in coastal areas. In: Schwartz, M. (Ed.), Encyclopedia of Coastal Science. Springer, Heidelberg, 226 pp.

Madgwick, F.J., Jones, T.A., 2002. Europe. In: Perrow, M.R., Davy, A.J. (Eds.), Handbook of Ecological Restoration. Restoration in Practice, vol. 2. Cambridge University Press, Cambridge, pp. 32–56.

MarLIN Glossary, 2005. The Marine Life Information Network for Britain and Ireland: Online Glossary of Scientific Terms. Available from: <http://www.marlin.ac.uk/Glossaries/Gen_Glossary.htm>.

McLusky, D.S., Elliott, M., 2004. The Estuarine Ecosystem: Ecology, Threats and Management, third ed. Oxford University Press, Oxford, 222 pp.

Morris, P., Therivel, R. (Eds.), 2001. Methods of Environmental Impact Assessment, second ed. Spon Press, London.

Perrow, M.R., Davy, A.J., 2002a. Handbook of Ecological Restoration. In: Principles of Restoration, vol. 1. Cambridge University Press, Cambridge, 444 pp.

Perrow, M.R., Davy, A.J., 2002b. Handbook of Ecological Restoration. In: Restoration in Practice, vol. 2. Cambridge University Press, Cambridge, 599 pp.

Peterson, G., 2000. Political ecology and ecological resilience: an integration of human and ecological dynamics. Ecological Economics 35, 323–336.

Pimm, S.L., 1984. The complexity and stability of ecosystems. Nature 307, 321–326.

Pratt, J.R., 1994. Artificial habitats and ecosystem restoration: managing for the future. Bulletin of Marine Science 55, 268–275.

Rogers, S.I., Greenaway, B., 2005. A UK perspective on the development of marine ecosystem indicators. Marine Pollution Bulletin 50, 9–19.

Rogers, S.I., Tasker, M.L., Earll, R., Gubbay, S., 2007. Ecosystem objectives to support the UK vision for the marine environment. Marine Pollution Bulletin 54, 128–144.

Ruiz-Jaen, M.C., Aide, T.M., 2005. Restoration success: how is it being measured? Restoration Ecology 13, 569–577.

Simenstad, C., Reed, D., Ford, M., 2006. When is restoration not? incorporating landscape-scale processes to restore self-sustaining ecosystems in coastal wetland restoration. Ecological Engineering 26, 27–39.

Society for Ecological Restoration, 1996. Ecological Restoration: Definition. Available from: <http://www.ser.org>.

Stillman, R.A., West, A.D., Goss-Custard, J.D., McGrorty, S., Frost, N.J., Morrisey, D.J., Kenny, A.J., Drewitt, A.L., 2005. Predicting site quality for shorebird communities: a case study on the Humber estuary, UK. Marine Ecology Progress Series 305, 203–217.

Tett, P., Gowen, R., Mills, D., Fernandes, T., Gilpin, L., Huxham, M., Kennington, K., Read, P., Service, M., Wilkinson, M., Malcolm, S., 2007. Defining and detecting undesirable disturbance in the context of eutrophication. Marine Pollution Bulletin 53, 282–297.

The Resilience Alliance, 2002. What is Resilience? Available from: <http://resalliance.org/ev_en.php?ID=1004_201&ID2=DO_TOPIC>.

Van Cleve, F.B., Leschine, T., Klinger, T., Simenstad, C., 2006. An evaluation of the influence of natural science in regional-scale restoration projects. Environmental Management 37, 367–379.

Walmsley, C.A., 2002. Beaches. In: Perrow, M.R., Davy, A.J. (Eds.), Handbook of Ecological Restoration. Restoration in Practice, vol. 2. Cambridge University Press, Cambridge, pp. 197–213.

Wood, C., 2003. Environmental Impact Assessment: A Comparative Review, second ed. Pearson Education Ltd., Harlow, England.

Yozzo, D.J., Clark, R., Curwen, N., Graybill, M.R., Reid, P., Rogal, K., Scanes, S., Tilbrook, C., 2000. Managed retreat: assessing the role of the human community in habitat restoration projects in the United Kingdom. Restoration Ecology 18, 234–244.

Zedler, J.B., 1984. Salt Marsh Restoration: A Guidebook for Southern California. California Sea Grant College, Institute of Marine Resources. University of California. California Sea Grant Report No. T-CSGCP-009.

Zedler, J.B., Adam, P., 2002. Salt marshes. In: Perrow, M.R., Davy, A.J. (Eds.), Handbook of Ecological Restoration. Restoration in Practice, vol. 2. Cambridge University Press, Cambridge, pp. 238–266.