# Marine ecosystem structure, functioning, health and management and potential approaches to marine ecosystem recovery: a synthesis of current understanding

Report to CCW

Institute of Estuarine and Coastal Studies
University of Hull

March 2006

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For and on behalf of the
Institute of Estuarine and Coastal Studies

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| Approved by: | ***Nick Cutts*** |
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| Position: | ***Deputy Director*** |
| Date: | ***March 2006*** |

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## CRYNODEB GWEITHREDOL

Mae Cynulliad Cenedlaethol Cymru wedi gofyn i Gyngor Cefn Gwlad Cymru (CCC) '*ddatblygu, gyda phartneriaid, y cysyniad o reoli'r amgylchedd morol trwy ddull yr ecosystemau, gan gynghori'n arbennig ar weithrediad ecosystemau morol o gwmpas Cymru, ynghyd â golwg ar eu cyflwr ac awgrymiadau ymarferol i sicrhau eu bod yn cael eu hamddiffyn a'u gwella*'. Mae'r adroddiad yma'n cynnig gwybodaeth i ategu'r cyngor y mae'r Cyngor Cefn Gwlad yn ei ddatblygu yn y cyswllt hwn. Mae'n cynrychioli prif amcanion project oedd â'r nod o adolygu a chyfuno'r ddealltwriaeth bresennol am:

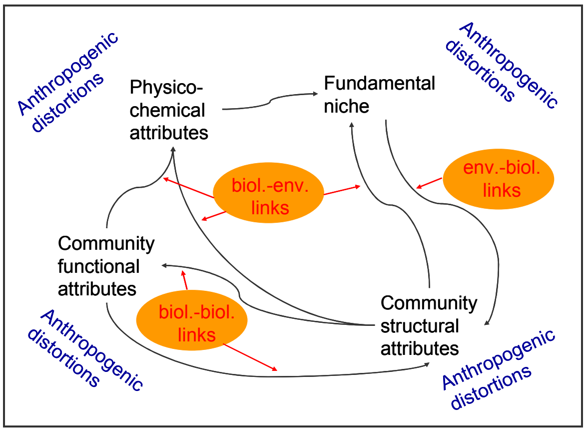
- weithrediad ecosystemau morol, a nodi a disgrifio dulliau i asesu eu gweithrediad, ynghyd â dulliau i fesur iechyd a gweithrediad ecosystemau morol ar arfordiroedd Cymru ac yn ei moroedd;
- adfer ecosystemau morol, ac awgrymu dulliau ymarferol o'u gwella (ar sail Dull yr Ecosystemau), y gellir eu datblygu ar arfordiroedd Cymru ac yn ei moroedd.

### Dull yr Ecosystemau a Strwythur a Gweithrediad Ecosystemau

Mae'r adroddiad yn cyflwyno'r prif nodweddion sy'n diffinio ecosystemau, gan ganolbwyntio ar weithredu Dull yr Ecosystemau o ran yr amgylchedd mrol. Mae'r dull yma'n edrych ar ffyrdd o reoli gweithredoedd dynol, a gellir edrych arno fel athroniaeth i grynhoi'r dulliau posibl o amddiffyn a chynnal ecosystemau wrth barhau i ganiatáu i'r gymdeithas eu defnyddio a'u datblygu mewn ffordd gynaliadwy. Mae'r adroddiad yn cyflwyno pwysigrwydd cynnyrch yr ecosystemau (e.e. pysgod, gwymon, tywod a graean) a'u gwasanaethau (e.e. cymedroli'r hinsawdd, cylchu maetholion a phuro llygryddion), sef pethau sy'n bwysig i'r gymdeithas. Mae angen i reolwyr arfordirol a'r bobl sy'n llunio polisïau arfer y dull yma am ei fod yn caniatáu i bobl nad ydynt yn wyddonwyr, budd-ddeiliaid a phobl eraill sydd â diddordeb weld a deall y cysylltiadau rhwng systemau dynol ac ecolegol.

Mae Rhan 2 o'r adroddiad yn cyflwyno'r derminoleg berthnasol a chysyniadau am strwythur a gweithrediad ecosystemau mewn perthynas â systemau morol. Mae'n dangos pwysigrwydd y gwahanol lefelau o ran trefniadaeth fiolegol (h.y. cell, unigolyn, poblogaeth, cymuned, ecosystem) ac o ran maint (gofodol ac amserol) wrth asesu strwythur a gweithrediad ecosystemau. Mae'r adroddiad yn canolbwyntio ar y prosesau sy'n creu ecosystemau morol, y cysylltiad rhwng y paramedrau amgylcheddol a biotig, ac ar y dylanwadau anthropogenig sy'n effeithio ar ecosystemau morol (gweler Ffigur ES-1).

Mae'r adroddiad yn trafod sut gellir dirywio a chyflwyno dirywiad iechyd a chyflwr y system forol, ac yn canolbwyntio ar allu'r systemau i ymateb i'r pethau sy'n rhoi pwysau arnynt. Am hynny, ystyrir bod ecosystem iach yn un sy'n gweithredu'n dda ac sy'n gallu gwrthsefyll aflonyddwch, neu wella ar ei ôl, sy'n nodwedd o wydnwch yn yr ecosystem.




**Ffigur ES-1:** Y cysylltiadau hanfodol sy'n creu ac yn addasu strwythur a gweithrediad yr ecosystem, sut y mae'r rhain yn mynd ymlaen i effeithio ar natur yr amgylchedd, a sut caiff dylanwad dynol ei arosod ar y perthnasau hyn.

Mae'r adroddiad yn parhau i ddiffinio'r prosesau morol critigol a hanfodol ac yn crynhoi dylanwad y newid anthropogenig ar y prosesau. Caiff y prosesau morol hanfodol eu rhannu'n hierarchaeth o 4 math: lefel 1 ('ffiisio-gemegol'), lefel 2 ('perthnasau biolegol a chyfryngiad'), lefel 3 ('dylanwadau anthropogenig') a lefel 4 ('ymatebion i newid'). Mae'r ddwy lefel gyntaf yn dylanwadu ar greu cynefinoedd biolegol, a strwythur a gweithrediad y gymuned, a gellir eu gweld yn eu trefn fel y pethau sy'n gyrru newid a'r pethau sy'n ymateb iddynt. Er enghraifft, y patrymau hydrograffig sy'n rheoli'r math o is-haen, a gallu'r organebau i gytrefu is-haenau penodol, yn y drefn honno. Yn groes i hynny, prosesau'r drydedd lefel yw'r rhai a ddylai gael eu hatal rhag difa iechyd biolegol y system. Er enghraifft, presenoldeb gwaith peirianneg sy'n aflonyddu ar y prosesau hydrograffig. Yn olaf, prosesau'r bedwaredd lefel yw'r mecanweithiau sydd eu hangen i adfer ecosystem neu i alluogi iddi ymadfer, neu i adfer ei chydrannau o fewn y defnydd cynaliadwy o gynnyrch yr ecosystem a'i gwasanaethau. Mae'r rhain yn cynnwys ail-greu cynefinoedd (a drafodir yn rhannau olaf yr adroddiad).

Mae'r adroddiad yn dangos y prif newidiadau i set benodol o gynefinoedd/ecosystemau sy'n bwysig yng nghyd-destun arfordiroedd a moroedd Cymru. Wedyn, caiff y wybodaeth ei chyflwyno ynghyd â'r nifer gynyddol o rymoedd sy'n gyrru'r polisïau a'r ddeddfwriaeth sydd eu hangen i gyflawni Dull yr Ecosystem, ac yn enwedig o fewn fframwaith Ewropeaidd. Trwy hynny, mae'r adroddiad yn rhoi gwybodaeth sy'n berthnasol i fabwysiadu Strategaeth Forol Ewrop, gweithredu'r Fframwaith Dŵr a Chyfeirebau eraill, Cyfeireb arfaethedig y Fframwaith Morol, a Mesur Morol arfaethedig y DU. Mae'r adroddiad yn cyflwyno dulliau rheoli ar sail gwerth yr amgylchedd morol, yn enwedig y fframwaith DPSIR (Grymoedd, Pwysau, Newid Cyflwr, Effeithiau ac Ymateb), y defnydd o amcanion a dangosyddion, a monitro ymatebion i'r newidiadau sy'n cael eu hachosi gan bobl. Yn y cyd-destun hwn, mae'r fframwaith DPSIR yn athroniaeth hwylus i esbonio beth sy'n achosi'r newid yn yr amgylchedd morol, a'r ymatebion ecolegol a chymdeithasol i'r newidiadau hynny gyda'r nod o leihau newidiadau andwyol mewn systemau morol.

**Adfer ac Unioni Ecosystemau**

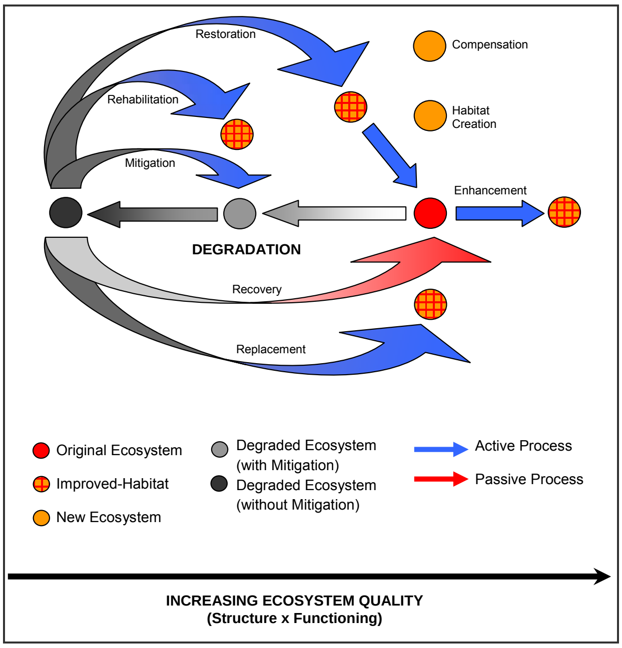
Mae Rhan 3 o'r adroddiad yn cyflwyno cysyniadau diweddar ynghyd â syniadau a phrofiadau cyfoes am adfer a chywiro ecosystemau aberol, arfordirol a morol.

Casgliad y dadansoddiad yw y gellir rhannu'r dulliau o adfer neu addasu'r cynefinoedd hyn trwy law dyn yn bedwar categori:

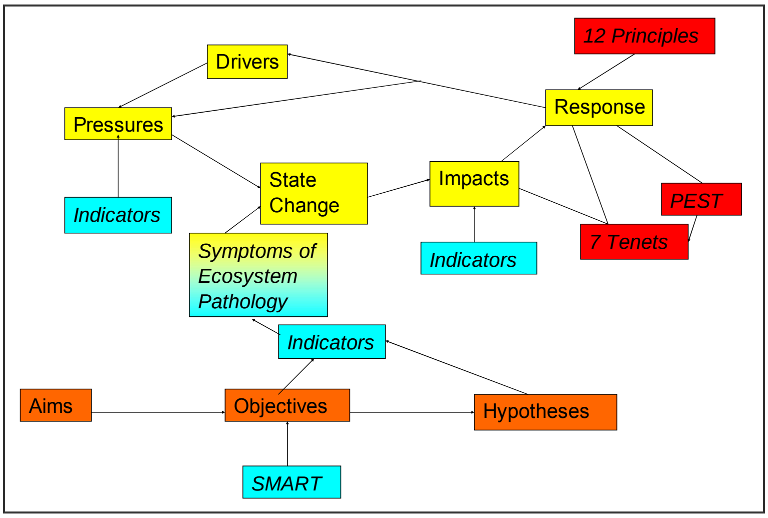
1. adferiad naturiol yn sgil newid naturiol neu anthropogenig (bod yn andwyol neu fel arall);
2. ymyrraeth anthropogenig mewn ymateb i amgylchedd sydd wedi cael ei ddiraddio neu ei newid mewn ffordd anthropogenigol;
3. ymatebion anthropogenig i un ffactor sy'n creu pwysau; a
4. gwella neu greu cynefinoedd.

Datblygwyd fframwaith cysyniadol ar gyfer adfer a gwella ardaloedd morol ymylol a lled-gaeedig (gweler Ffigur ES-2) ar ôl edrych ar y llu o ymadroddion a ddefnyddiwyd ym maes gwyddoniaeth a rheoli adferiad. Yn dilyn adolygiad cyflym o'r ddeddfwriaeth a'r grymoedd y tu ôl i bolisïau adfer, mae'r adroddiad yn rhoi amrywiaeth o ymatebion rheoli, gan gynnwys ailosod dan reolaeth, adfer dociau, adfer creigresi, morfeydd heli, morwellt a thraethau biogenig, ac adfer ansawdd dŵr parthau uwch aberoedd. Felly mae'r profiad hwn yn berthnasol ac yn werthfawr yng nghyd-destun Cymru. Er bod technegau adfer gweithredol yn werthfawr os oes modd eu cyflawni, mae'r adroddiad yn pwysleisio mai pur anaml (os o gwbl) y gallant gymryd lle'r cynefin a gollwyd yn llwyr. At hynny, mae'r adroddiad yn dangos, er bod y dulliau hyn yn mwynhau rhywfaint o lwyddiant mewn ardaloedd ymylol neu led-gaeedig fel baeau arfordirol, aberoedd a chynefinoedd ymylol, maen nhw'n llai perthnasol i gynefinoedd arfordirol a morol agored. Y casgliad felly, yw mai'r dewis gorau sydd ar gael yn yr amgylchedd morol, yw cael gwared ar y peth sy'n achosi'r pwysau, fel achos unrhyw newid, atal pwysau eraill a chaniatáu ar gyfer amodau sy'n addas ar gyfer adferiad naturiol.

Casgliad yr adroddiad yw, er bod rhai cysyniadau ecolegol yn hawdd eu deall, er enghraifft natur a gweithrediad ecosystemau, mae'r ddarpariaeth ar gyfer eraill, fel baich y pwysau, gwydnwch a chynnyrch a gwasanaethau'r ecosystem, yn dal i fod yn wael yn yr amgylchedd morol. Mae'r cysylltiad rhwng y cysyniadau ecolegol hyn a'r fframwaith rheoli'n dal i fod yn beth gymharol ddiweddar er, fel y mae'r adroddiad yma'n ei ddangos, mae'r cysyniadau'n cael eu hintegreiddio i greu dull cyfannol o ddeall, trin a rheoli'r amgylchedd morol erbyn heddiw (gweler Ffigur ES-3).




**Ffigur ES-2:** Model cysyniadol sy'n dangos natur adferiad natruiol ecosystem sydd wedi dirywio a'r amodau ar gyfer adferiad (gweithredol) trwy law dyn. Mae'r model yn dangos y gellir cynhyrchu cynefinoedd, ( ) sy'n gwella ar y cyflwr ar ôl y dirywiad, ond nad ydynt o reidrwydd yn cyrraedd eu cyflwr gwreiddiol ( ), tra bod ecosystemau eraill ( ) yn creu systemau hollol newydd. Gall yr adferiad (saeth goch) fod i'r cyflwr gwreiddiol neu fynd rhywfaint o'r ffordd i adennill ansawdd yr ecosystem. Mae'r model yn pwysleisio'r ffordd y mae ecosystemau'n symud ar hyd continwwm (echel lorweddol) o ansawdd ecosystemau, sy'n cyfuno strwythur a gweithrediad, ond nid oes unrhyw arwyddocâd i safle'r ecosystemau ar yr echel fertigol.




**Ffigur ES-3:** Model cysyniadol sy'n dangos sail Dull yr Ecosystem lle (i) mae dyn yn defnyddio'r systemau morol, daw eu heffeithiau a'u hymatebion cymdeithasol trwy'r athroniaeth DPSIR, (ii) mae pwyso a mesur achosion y newid ac ymatebion y systemau naturiol a dynol yn gofyn am ddangosyddion meintiol sy'n gysylltiedig â monitro a rheoli, (iii) bod y broses yn gofyn am wyddoniaeth dda ar sail nodi amcanion y system forol a phrofi damcaniaethau, a (iv) mae'r ymatebion cyffredinol i greu system forol gynaladwy yn gofyn am integreiddio agweddau amgylcheddol, technolegol a chymdeithasol (gweinyddol, gwleidyddol, economaidd a deddfwriaethol) fel y mae egwyddorion Dull yr Ecosystem ac athroniaethau PEST a 7-Tenet yn ei ddangos.

Er bod yr adroddiad hwn wedi nodi'r agweddau cyffredinol sy'n berthnasol i bob ardal forol, mae pob un o'r agweddau a drafodwyd yn galw am ystyriaeth bellach mewn perthynas â'r pwysau a'r effeithiau arbennig ar hyd arfordir Cymru ac allan yn y Môr Celtaidd. Mae'r project wedi nodi dewisiadau ar gyfer adfer gwahanol fathau o gynefinoedd ac ardaloedd, ond mae angen catalogio arfordir Cymru a'r môr mewn perthynas â dirywiad y cynefinoedd o hyd. Bydd catalogio fel hyn yn y dyfodol yn gosod yr angen am adfer yn ei gyd-destun ac yn nodi'r union ddulliau ar gyfer pob ardal.

**Dulliau Rheoli Morol**

Mae Adran 4 o'r adroddiad yn crynhoi dulliau a mentrau rheoli morol diweddar a chyfoes ac mae'n dangos bod yna gefndir rhagorol o wybodaeth i gysylltu'r elfennau hyn. Mae'r rhain yn cynnwys yr asesiad o Bwysau ac Effeithiau WFD a gyflawnodd Asiantaeth yr Amgylchedd, Strategaeth Forol Asiantaeth yr Amgylchedd, yr ymarfer Tirweddau Morol i osod ffiniau biotopau a gyflawnodd y Cyngor Cefn Gwlad, y project Cynllunio Gofod Morol a wnaed ar ran Defra, a'r project parthau morol a gyflawnodd IECS ar gyfer project Arbrofol y Môr Celtaidd. Mae'r adroddiad yn trafod yr angen am amcanion, dangosyddion a strategaethau monitro morol a'u natur, ac enghreifftiau ohonynt. Er nad yw'r gyfres o amcanion a dangosyddion ar gyfer dyfroedd Cymru wedi cael ei llunio eto, caiff y gwaith ei wneud yn sgil projectau sy'n edrych ar Ysgafell Gyfandirol y DU cyfan. Felly mae llwyth o wybodaeth gyffredinol a phenodol ar gael am ardal forol Cymru, gan gynnwys ei harfordiroedd a'i haberoedd, a gellir defnyddio'r wybodaeth hon i lunio dull mwy integredig a thraws-sectoraidd o weithio. Bydd y ffynonellau gwybodaeth hyn yn caniatáu ar gyfer gosod y dewisiadau rheoli mewn perthynas â'r ddealltwriaeth am y prosesau a'r effeithiau pennaf, yng nghyd-destun Cymru, y DU ac Ewrop. Am hynny, mae'r adroddiad yn cyflwyno cysyniadau sy'n gofyn am gael eu defnyddio ar lefelau biodaearmorphig sy'n briodol ar gyfer ardaloedd morol Cymru.

Y casgliad yw bod yr adroddiad presennol yn canolbwyntio ar ddarparu gwybodaeth am y newid o 'ddull yr ecosystemau' i 'Ddull yr Ecosystemau', sef dull strwythuredig o weithio sy'n edrych ar ddarlun mawr nodweddion morol, nodweddion strwythurol a swyddogaethol, ac ymatebion ecolegol a chymdeithasol i bwysau anthropogenig. Mae'r adroddiad yn dangos pa mor gymhleth yw gwyddoniaeth y system forol a'r rheolaeth y mae hyn yn ei fynnu, ond mae'n dangos bod yna ddealltwriaeth dda o'r agweddau hyn hefyd. At hynny, mae'n pwysleisio bod gan gyrff yng Nghymru gyfoeth o wybodaeth sy'n addas i roi Dull yr Ecosystemau ar waith. Y casgliad pellach yw y bydd y dulliau llywodraethu morol sydd ohoni, fel agweddau deddfwriaethol a gweinyddol, ar lefel rhanbarthol, cenedlaethol, Ewropeaidd a rhyngwladol, yn caniatáu ar gyfer dull cyfannol o weithio, ond bydd yn gofyn bod cyrff y llywodraeth a chyrff statudol yn gyfarwydd â rheolaeth amgylcheddol forol, nid yn unig yn nhermau ecoleg, ond hefyd yn nhermau cymdeithasol.

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## EXECUTIVE SUMMARY

The National Assembly of Wales has asked the Countryside Council for Wales (CCW) to '*develop with partners, the concept of an ecosystem approach to the management of the marine environment, specifically advising on the functioning of marine ecosystems around Wales together with a view on their condition and practical suggestions for securing their protection and recovery*'. This report provides information to support the development of the advice to be provided by CCW in this context. It presents the main objectives of a project which aimed to review and synthesise the current understanding of:

- marine ecosystem functioning, and to identify and illustrate methods for the assessment of ecosystem function, and approaches by which the health of marine ecosystem functioning around Welsh coasts and seas can be judged;

- the recovery of marine ecosystems, and to suggest practical approaches for recovery (based upon the Ecosystem Approach), that may be taken forward around Welsh coasts and seas.

### The Ecosystem Approach and Ecosystem Structure and Functioning

The main features defining ecosystems are presented and the report centres on the application of the Ecosystem Approach for the marine environment. This approach considers the management of human activities and can be regarded as a philosophy for summarising the means by which the natural functioning of an ecosystem can be protected and maintained while still allowing and delivering sustainable use and development by society. The report introduces the importance of ecosystem goods (e.g. fish, seaweed, sand and gravel resources) and services (e.g. climate regulation, nutrient cycling and contaminant purification) which are of societal value. This approach is required by coastal managers and policy makers as it allows the linkages between human and ecological systems to be understood by non-scientists, stakeholders and other interested parties.

Section 2 of the report introduces the relevant terminology and concepts of ecosystem structure and functioning with respect to marine systems. It identifies the importance both of the different levels of biological organisation (i.e. cell, individual, population, community, ecosystem) and of scale (both spatially and temporally) when assessing ecosystem structure and functioning. The report concentrates on the processes which create marine ecosystems, the links between the environmental and biotic parameters and on the anthropogenic influences affecting marine ecosystems (see Figure ES-1).

The report discusses the way in which the deterioration in the health and condition of the marine system is analysed and presented, and focuses on the ability of the systems to respond to stressors. As such, a healthy ecosystem is considered to be one that functions well and has the capability to resist, or recover from, disturbance, a feature which is regarded as the resilience in the ecosystem.

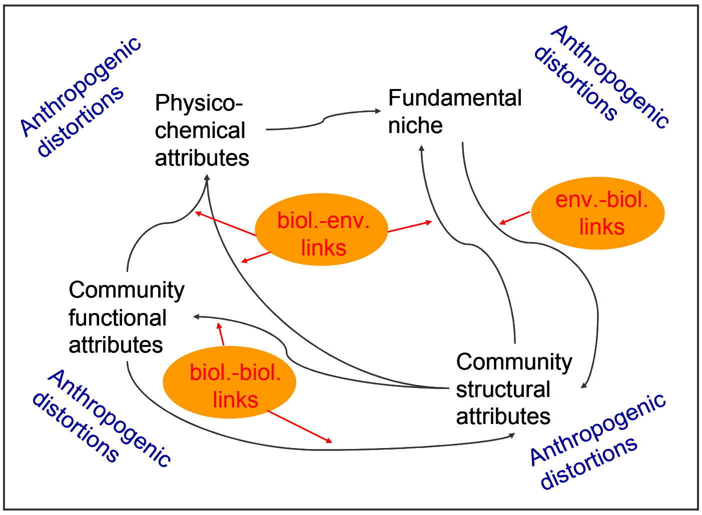


**Figure ES-1:** The fundamental links which create and modify the ecosystem structure and functioning, the way in which these then affect the nature of the environment, and the way in which human influences are superimposed on these relationships.

The report then goes on to define the critical and fundamental marine processes and summarises the influence of anthropogenic change on those processes. These fundamental marine processes are divided hierarchically into 4 types: level 1 ('physico-chemical'), level 2 ('biological inter-relationships and mediation'), level 3 ('anthropogenic influences') and level 4 ('responses to change'). The first two levels influence the creation of biological habitats and the community structure and functioning and so can be regarded respectively as drivers and responses to those drivers. For example, respectively the hydrographic patterns which control the substratum type, and the ability of organisms to colonise specific substrata. In contrast, the third level processes are those which should be prevented otherwise there will be a reduction of the biological health of the system. For example, the interference of hydrographic processes by the presence of engineering constructions. Finally, the fourth level processes are those mechanisms required to enable an ecosystem to recover or needed to restore it or its components but within the sustainable use of the ecosystem goods and its services. These include habitat re-creation (covered in the later sections of the report).

The report indicates the main changes to a given set of habitats/ecosystems which are important in a Welsh coastal and marine context. This information is then presented together with the growing number of major policy and legislative drivers necessary for delivering the Ecosystem Approach, especially within a European framework. As such the report gives information relevant to the adoption of the European Marine Strategy, the implementation of the Water Framework and other Directives, the proposed Marine Framework Directive and the proposed UK Marine Bill. The report gives management approaches of value for the marine environment, in particular the DPSIR (Drivers, Pressures, State change, Impacts and Response) framework, the use of objectives and indicators, and monitoring responses to human-induced change. In this context, the DPSIR framework is a convenient philosophy for explaining the causes of change in the marine environment and the ecological and societal responses to those changes, with the latter aimed at minimising deleterious change in the marine system.

**Ecosystem Recovery and Restoration**

Section 3 of the report presents recent concepts and the current understanding and experience of the restoration and recovery of estuarine, coastal and marine ecosystems. The analysis has concluded that the recovery or human-mediated modification of these 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.

A conceptual framework for restoration and recovery of marine marginal and semi-enclosed areas has been developed (see Figure ES-2) after exploring the plethora of terms used in restoration science and management. Following a brief review of the legislation and policy drivers for restoration, the report gives various examples of management action including managed realignment, the restoration of docks, the restoration of biogenic reefs, saltmarsh, seagrass and beaches, and the restoration of upper estuarine water quality. This experience is then of value and relevance for use in a Welsh context. The report emphasises that although active recovery techniques are certainly worthwhile if they can be carried out, they rarely (if ever) fully replace lost habitat. Moreover, as shown by the report, 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. Hence, it is concluded that the best option available in the marine environment can only be to remove the stressor, as the cause of any change, to prevent other stressors and to allow the conditions suitable for natural recovery.

The report concludes that whereas some ecological concepts 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 environment. The linking between these ecological concepts and the management framework is also relatively recent although, as shown in the report, the concepts are now being integrated to give an holistic approach to understanding, manipulating and managing the marine environment (see Figure ES-3).

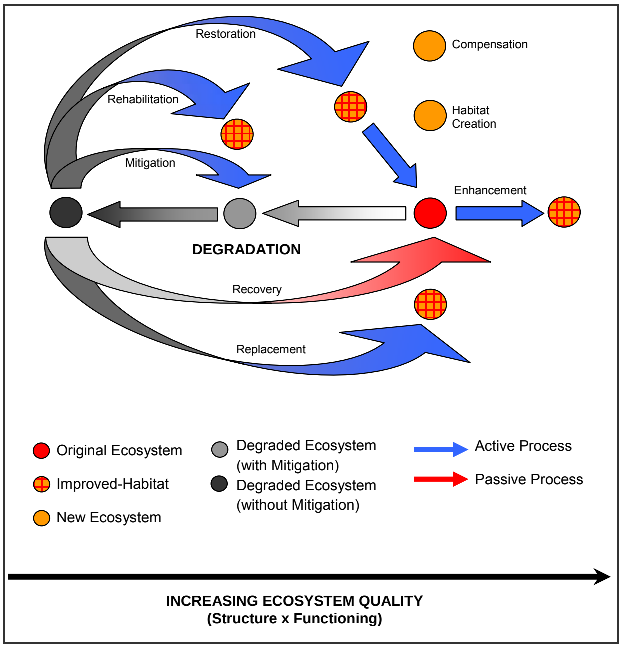


**Figure ES-2:** A conceptual model illustrating the nature of natural recovery of a degraded ecosystem and the terms used in human-mediated (active) restoration. The model indicates that habitats can be produced ( ) which are an improvement on the degraded state but not necessarily to the original state ( ), whereas other ecosystems ( ) are newly created systems. The recovery (red 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.

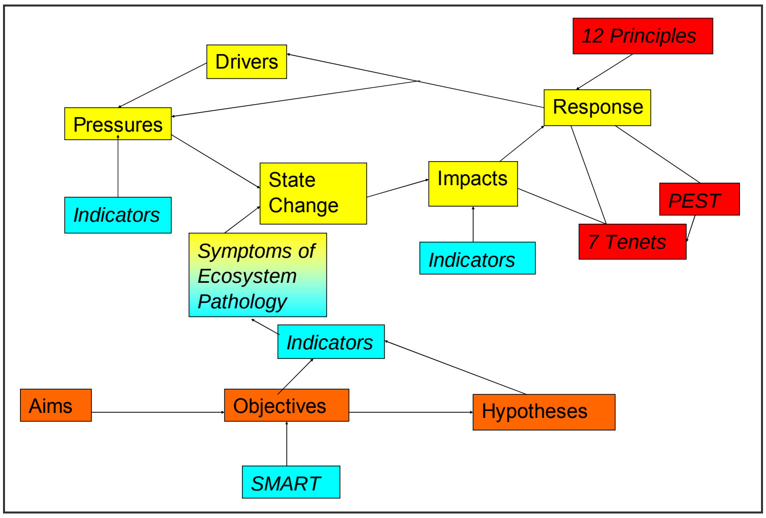


**Figure ES-3:** A conceptual model illustrating the basis of the Ecosystem Approach in which, (i) the human uses of the marine systems, their effects and societal responses are given by the DPSIR philosophy, (ii) the determination of causes of change and responses by the natural and human system requires quantitative indicators linked to monitoring and management, (iii) that the process requires good science based on the stating of objectives for the marine system and testing of hypotheses, and (iv) the overall responses to achieve a sustainable marine system requires the integration of environmental, technological and societal (administrative, political, economical and legislative) aspects as shown by the principles of the Ecosystem Approach and the PEST and 7-Tenet philosophies.

While this report has given the generic aspects relative to all marine areas, each of the aspects discussed requires further consideration in relation to the particular pressures and impacts along the Welsh coast and the offshore Irish Sea area. The present project has identified options for restoring various types of habitat and area but a cataloguing of the Welsh coastline and sea area with regard to the degraded status of the habitats is still required. A future cataloguing of this type will both put into perspective the need for restoration and identify the precise approach for each area.

**Marine Management Approaches**

Section 4 of the report summarises the recent and present marine management approaches and initiatives and shows that there is an excellent background of information to link the above aspects. These include the WFD Pressures and Impacts assessment carried out by the Environment Agency, the Environment Agency's Marine Strategy, the Marine Landscapes and biotope delimitation carried out by CCW, the shore SAC cataloguing carried out by CCW, the Marine Spatial Planning project carried out for Defra, and the marine zoning project carried out by IECS for the Irish Sea Pilot project. The report discusses the need for, and nature and examples of marine objectives, indicators and monitoring strategies. While the suite of objectives and indicators has not yet been derived for Welsh waters, this will occur as the result of projects considering the whole of the UK Continental Shelf. Hence, there is a large amount of information both generic and specific to the Welsh marine area, including its coastlines and estuaries, which can be used to produce a more integrated, cross-sectoral approach. These sources of information will allow management options to be superimposed on the understanding of dominant processes and impacts in a Welsh, UK and European context. As such the report presents concepts which require to be used at relevant biogeomorphic scales for Welsh marine areas.

It is concluded that the present report centres on providing knowledge of the transition from 'an ecosystem approach' to 'The Ecosystem Approach', a structured approach which takes a wide view of marine characteristics, structural and functioning attributes, and ecological and societal responses to anthropogenic stressors. The report shows the complexity both of the science of the marine system and the management required for it but indicates that there is a good understanding of these aspects. Furthermore, it emphasises that the bodies within Wales have a wealth of information suitable for implementing the Ecosystem Approach. It is further concluded that the prevailing marine governance, as legislative and administrative aspects, at regional, national, European and international levels, will also allow an holistic approach but will require the government and statutory bodies to be familiar with marine environmental management not only in ecological terms but also in societal ones.

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## TABLE OF CONTENTS

# 1. INTRODUCTION AND OVERVIEW

This report aims to provide a synthesis of current understanding with regard to marine ecosystem functioning, the assessment of functioning, the influence of human activities on that structure and functioning, and the potential approaches to marine ecosystem recovery. Key terms and concepts are presented (**in bold**) and defined within the text where possible but also within a glossary appended to this report. While the report presents information relevant to all marine ecosystems, where necessary it highlights features specifically related to the ecosystems that are in and around Welsh seas and coasts.

The project was undertaken as two related desk-based work packages: the first concerning the functioning of marine ecosystems, and the second focussing on the recovery of marine ecosystems. As such, the main objectives were to:

- review and synthesise the current understanding of marine ecosystem functioning, to identify and illustrate methods for the assessment of ecosystem function, and approaches by which the health of marine ecosystem functioning around Welsh coasts and seas can be judged (Work Package 1);

- review and synthesise the current understanding of approaches to the recovery of marine ecosystems, and to suggest approaches for practical recovery (based upon the Ecosystem Approach), that may be taken forward around Welsh coasts and seas (Work Package 2).

The Countryside Council for Wales (CCW) has been asked by the National Assembly for Wales to '*develop with partners, the concept of an ecosystem approach to the management of the marine environment, specifically advising on the functioning of marine ecosystems around Wales together with a view on their condition and practical suggestions for securing their protection and recovery*'. It is of note that the Welsh Assembly Government has recognised the importance of the marine environment in its Environment Strategy consultation document and so this report provides information to support the development of the advice provided by CCW in this context.

## 1.1 Structure of the Report

The present report introduces the topics of ecosystem features, the determination of ecosystem and biological health, recent legislative and policy drivers and management philosophies, and the science and understanding behind the restoration of marine ecosystems. Section 1 introduces the overall topics and gives a brief policy overview. Section 2 defines the ecosystem principles, approach and features as well as presenting more detail regarding ecosystem health and symptoms of change due to human activities. Following this, Section 3 discusses ecosystem recovery and restoration, again by presenting, defining and discussing the various topics. Section 4 gives recent management concepts both within the scientific and ecological context of maintaining and protecting marine environmental health and also within a societal context. The final section 5 presents a discussion and set of recommendations based on recent concepts in the management of marine systems that are relevant in the context of the current report. Based on the identification of impacts on ecosystem functioning, the report identifies potential remediation or restoration measures that can be employed in a Welsh context.

## 1.2 Underlying Concepts: The Ecosystem Approach, Ecosystem Goods and Services and the DPSIR Philosophy

Ecologists have long discussed *an ecosystem approach* as a concept in the study and understanding of ecosystems and thus a fundamental part of ecology (e.g. Likens, 1992). However, more recently this has become ***The Ecosystem Approach*** as a philosophy for understanding and managing the human uses and effects on systems. As such, the term now appears in many management and policy documents such as from the FAO, OSPAR, the EC Directives and nature conservation reports (e.g. FAO, 2003; Pope & Symes, 2000a; Pope & Symes, 2000b; Laffoley *et al.*, 2004; ICES, 2005). It encourages the consideration and management of human activities and can be regarded as a philosophy for summarising the means by which the natural functioning of an ecosystem can be protected and maintained while still allowing and delivering sustainable use and development by society.

At its most comprehensive, the concept of the Ecosystem Approach has been further defined and expanded by The Convention for Biological Diversity (CBD, 2000) as:

'*a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. The application of the Ecosystem Approach will help to reach a balance of the three objectives of the Convention: conservation, sustainable use and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources*'.

As such, the Ecosystem Approach also requires an understanding of the way in which society manages the adverse effects of its activities, including mitigation and/or compensation. The present review assesses the adverse effects of human activities on natural resources in general, genetic or otherwise. In order to achieve that sustainable management, the Convention for Biological Diversity indicates that the implementation of the Ecosystem Approach should be based upon 12 guiding principles (see Box 1).

**Box 1: Twelve principles of the Ecosystem Approach (CBD, 2000)**

1. The objectives of management of land, water and living resources are a matter of societal choices.
2. Management should be decentralised to the lowest appropriate level.
3. Ecosystem managers should consider the effects (actual or potential) of their activities on adjacent and other ecosystems.
4. Recognising potential gains from management, there is usually a need to understand and manage the ecosystem in an economic context. Any such ecosystem-management programme should: a) Reduce those market distortions that adversely affect biological diversity; b) Align incentives to promote biodiversity conservation and sustainable use; c) Internalise costs and benefits in the given ecosystem to the extent feasible.
5. Conservation of ecosystem structure and functioning, in order to maintain ecosystem services, should be a priority target of the ecosystem approach.
6. Ecosystem must be managed within the limits of their functioning.
7. The ecosystem approach should be undertaken at the appropriate spatial and temporal scales.
8. Recognising the varying temporal scales and lag-effects that characterize ecosystem processes, objectives for ecosystem management should be set for the long term.
9. Management must recognise that change is inevitable.
10. The ecosystem approach should seek the appropriate balance between, and integration of, conservation and use of biological diversity.
11. The ecosystem approach should consider all forms of relevant information, including scientific and indigenous and local knowledge, innovations and practices.
12. The ecosystem approach should involve all relevant sectors of society and scientific disciplines.

### 1.2.1 Ecosystem Goods and Services

***Ecosystem goods and services*** can be taken to include natural components or, more commonly at present, features of some use by Man. The marine and estuarine ecosystems and their biological diversity deliver a set of goods and services which remain essential to Man's economic prosperity and other aspects of our welfare (Eftec, 2005). The concept of ecosystem goods and services is of value to coastal managers and policy makers as it allows the linkages between human and ecological systems to be understood by non-scientists, stakeholders and other interested parties.

***Ecosystem services*** can be defined as '*the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life*' (Daily, 1997). For example, in the marine environment ecosystem services include maintaining hydrological cycles, regulating climate, contaminant purification, and storing and cycling essential nutrients such as nitrogen and phosphorus. In contrast, ***ecosystem goods*** '*represent the materials produced that are obtained from natural systems for human use*' (De Groot *et al.*, 2002). Examples in the marine environment include biological and non-biological materials such as food (such as fish/shellfish, seaweeds), building materials (such as sand and gravels), and medicinal products from marine plants, microbes and animals.

The definition can be expanded to include recent uses and resources from the marine environment such as marine renewable energy, i.e. from offshore wind and wave power. These examples demonstrate that ecosystem services occur at different scales, for example climate regulation and carbon sequestration occur at a global level, whereas waste treatment occurs at a local or regional scale (De Groot *et al.*, 2002).

Ecosystem goods and services are particularly abundant in coastal systems. These goods and services, and the natural capital stocks that produce them, are critical to the functioning of the earth's life-support systems (Costanza *et al.*, 1997). Recently, there have been many studies on the valuation of goods and services provided by coastal systems (e.g. see De Groot, 1992; Daily, 1997; Costanza *et al.*, 1997) although references to valuing goods and services within the literature date from the mid-1960s and early 1970s (see for example King, 1966 and Odum & Odum, 1972; as cited in De Groot *et al.*, 2002). Ecosystem goods and services contribute to human welfare, both directly and indirectly, and therefore represent part of the total global economic value (Costanza *et al.*, 1997). These issues are currently being addressed within the scope of an ongoing European project, MarBEF, which aims to investigate marine biodiversity and ecosystem functioning (http://www.marbef.org/).

## 1.3 Habitat and Ecosystem Restoration

Given that estuarine, coastal and marine habitats and ecosystems have been adversely affected by human activities, there is the need to implement ***restoration***, ***remediation*** and ***re-creation*** schemes - this constitutes the Response part of the DPSIR framework (see below). While there is an extensive body of literature and experience relating to terrestrial and freshwater systems (e.g. Perrow & 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; 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 and can be carried out for open marine systems other than to remove the stressor (Hawkins *et al.*, 1999, 2002).

As shown in this report (Section 3), the semantics of restoration are detailed and thus in some literature confusing with unnecessary separation and interpretations of the terms. Restoration should be widely taken '*as 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). This requires a consideration of:

- 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;
- whether the system is to be restored to a pristine state or merely fit-for-purpose;

- whether there are some human impacts which are unavoidable; and
- what are the human impacts against a background of natural and wider change, such as global climate change.

## 1.4 The DPSIR Approach, Indicators of Change and the Management Framework

The ***DPSIR approach*** has been used as a framework in order to assess the causes, consequences and responses to change. This identifies 'Drivers' of change leading to individual 'Pressures' causing 'State change' in the marine system. In turn, these lead to 'Impacts' on the human system which then require a 'Response' under which the problems or potential problems are addressed. In particular this is related to ecosystem disturbance which has been defined by Perrow & Davy (2002b) '*an event or series of events that change the relationships between organisms and their habitats from their natural states, both spatially and temporally*' and presumably as the result of human activities.

The DPSIR approach allows pathways and symptoms of change to be identified, together with an assessment of the mechanisms of response such as the implementation of European directives, e.g. the Water Framework Directive (WFD), the EC Habitats Directive and the Wild Birds Directive (see Section 1.5) all of which concentrate on structural components rather than functional responses (De Jonge *et al.*, 2006). For example, in the case of the WFD, assessments are required to assess changes to the ecological status of the phytoplankton, macroalgae, macrophytes, benthic macrofauna and, for transitional waters such as estuaries, fishes. These components relate to the 'State Change' and 'Impact' aspects of the DPSIR approach (Box 2) against a background of the 'Drivers' and 'Pressures' of these biogeomorphic units such as water bodies. The Ecosystem Processes are predominantly included in the categories State Change and Impact, hence Section 2 of this report details concepts related to the health of the system and damage caused to the ecological components.

Section 4 of the report details the links between the ecological aspects and the societal aspects and thus puts the discussions within a socio-economic, political and legislative framework. This requires an holistic view to be taken which links ecological change to objectives, indicators, monitoring and management systems which are embedded within the prevailing marine governance framework. In particular, for ecosystems to be managed requires:

- both the over-riding and more detailed and precise objectives to be set for the area;
- quantitative indicators of natural and anthropogenic change to be derived;
- monitoring systems to be put in place to determine if the objectives and indicators have been met; and
- management responses identified to ensure actions are taken if the objectives and indicators are not met (see Section 2).

**Box 2: The DPSIR approach (see also McLusky & Elliott, 2004)**

| |
|---|
| ***D**riving forces:*<br>(human activities and economic sectors responsible for the pressures) e.g. urban developments;<br><br>***P**ressures*:<br>(particular stressors on the environment in the form of direct pressures such as emissions) e.g. sewage discharges, increased organic inputs;<br><br>***S**tate change*:<br>(changes in environmental variables (geo/physical/chemical/biological) which describe the characteristics and conditions of the coastal zone); these changes occur in both structural components and functioning processes, e.g. reduced oxygen levels, increased water turbidity, degraded communities;<br><br>***I**mpact*:<br>(changes in the ecosystem resources affecting human uses and health) e.g. loss of amenity areas, fisheries populations, eutrophication, reduced biodiversity;<br><br>***R**esponse*:<br>(measurement of different policy options as a response to the environmental problems) e.g. economic and legislative instruments, the actions following the use of indicators. |

## 1.5 Underpinning European Legislation and Policy Drivers

The Millennium Assessment (http://millenniumassessment.org/en/index.htm) recently summarised the way in which human activities disrupt natural processes and thus emphasised the need for legislation and policy drivers to control those adverse effects. That legislation and policy forms the dominant part of the Response in the DPSIR framework which in turn should control the Drivers and Pressures which cause environmental change. As a result of considerable international and national policies aimed at delivering improved protection for the marine environment, there are currently several policy drivers which require the application of the Ecosystem Approach to the management of the marine environment. The definition and use of the principles of the Ecosystem Approach were endorsed under the ***Convention of Biological Diversity*** as the primary framework for promoting the management, conservation and sustainable use of natural resources[1].

There are several policy drivers which focus attention on the need to target protection measures on the ecosystem processes that support biodiversity and, as a result, the Ecosystem Approach requires that '*conservation of ecosystem structure and functioning, in order to maintain ecosystem services, should be a priority target*'[2]. In its report to Government during 2004, the Review of Marine Nature Conservation (Defra, 2004a) recommended that the current situation where protection is primarily site specific and based on special species and habitats, should be taken forward to encompass a more holistic, functionally-based approach. It is of note that although Defra emphasises that biodiversity protection is a key government priority, its biodiversity research advisory group considers

[1] Decision V/6 of the CBD Conference of Parties, 2000 - www.biodiv.org/programmes/cross-cutting/ecosystem/default.asp

[2] A principle of the Ecosystem Approach outlined by the Convention on Biological Diversity, 2000.

this area to be under-researched (Dr M. Kaiser, University of Wales, Bangor, pers. comm.). Furthermore, in their Marine Strategy, the Environment Agency (2005b) presents their assessment of the state of the coasts and seas of England and Wales and emphasises the policy underpinning their activities, the central role of the Water Framework, and the role of the other environmental quality EU Directives. They emphasise the need to take the ecosystem approach and thus a wide and holistic view of the marine environment, its features and threats all of which should be underpinned by good and adequate science. The Agency also acknowledges the importance of working with other statutory bodies and stakeholders.

In addition to focussing on ecosystem functioning, several regulatory frameworks have been developed to protect marine ecosystems, and where possible, promote their recovery. While those regulatory frameworks, the legislation and its enforcement are detailed elsewhere (Bell & McGillivray, 2006; Boyes *et al.*, 2003a), the most important and wide-ranging primary legislation relating to this has been or is being produced by the European Commission. The earlier EC Directives can be regarded as focussing on sectoral aspects or single problems, such as the directives for the Titanium Dioxide industry, Bathing Waters' Quality, Urban Waste Water Treatment, Shellfish Growing Waters and Shellfish Hygiene (Apitz *et al.*, 2006). Of more relevance here is the recent move towards holistic directives which aim to address the quality and management of ecosystems from several or all human influences, for example:

- the ***Habitats Directive***, which requires member states to maintain, restore, and avoid deterioration of natural habitats and to ensure their Favourable Conservation Status; to carry out an Appropriate Assessment of plans and projects likely to adversely affect the identified conservation features (habitats and species);

- the ***Wild Birds Directive***, which requires member states to classify Special Protected Areas (SPAs) to conserve the habitats of rare and vulnerable species, and of regularly occurring migratory species, to ensure their survival and reproduction in their area of distribution;

- the ***Environmental Impact Assessment (EIA) Directive***, which requires member states to put into place procedures for the EIA of certain public and private projects, before they are authorised in order to ensure that all projects that are likely to have significant environmental effects are assessed;

- the ***Strategic Environmental Assessment (SEA) Directive***, which requires member states to provide for a high level of protection of the environment by ensuring that an environmental assessment is carried out of certain plans and programmes and that the results of the assessment are taken into account during the preparation and adoption of such plans and programmes;

- The ***Integrated Pollution Prevention and Control (IPPC) Directive***, which requires member states to prevent, or when that is not practicable, to reduce emissions to air and water in order to achieve a high level of protection of the environment as a whole;

- The ***Nitrates Directive***, which requires member states to reduce water pollution that is caused or induced by nitrates from agricultural sources and to prevent further pollution of this type;

- The ***Environmental Liability Directive***, which requires member states to apply the '***polluter pays principle***' so that those causing damage to the environment (water, land, and nature) are legally and financially responsible for that damage;

- the ***Water Framework Directive,*** which requires member states to achieve a Good Ecological Status for all surface waters by 2015;

- and the ***EC Marine Strategy*** (EC, 2005a) and the recently proposed (October 2005) ***Marine Strategy Framework Directive*** (EC, 2005b), which aim to provide a framework which includes the restoration of marine ecosystems and the requirement to achieve Good Environmental Status by 2021 amongst their objectives.

The above paragraphs merely present the predominant statutory and regulatory drivers as produced by the European Commission and agreed by the European Union. Each of these is accompanied by enabling legislation which allows the Directives to be transcribed into UK legislation. The regional, national, European and international legislation and agreements is described fully in the reports produced by the Institute of Estuarine & Coastal Studies for the Irish Sea Pilot Project and so not repeated here (Boyes *et al.*, 2003a, b, c, d). It is of note that this legislative and administrative framework provides the UK commitment to the agreements made at the World Summits on Sustainable Development (Rio de Janeiro 1992, New York 1995 and Johannesburg 2002).

Almost 30% of ***Welsh waters*** have been designated as ***Special Areas of Conservation (SACs)*** under the Habitats Directive and the WFD is being implemented to one nautical mile in England & Wales (and 3 nautical miles in Scotland). Because of this, there will be an increasing need to consider the management of whole estuarine and coastal ecosystems. In addition, a Marine Strategy Framework Directive would extend this management and protection to the remainder of UK marine waters (out to 200 nautical miles). Similarly, the long-established convention, the ***OSPAR Convention***, has progressed from the consideration of pollution from land-based and vessel discharges (respectively the Paris and Oslo conventions which were merged in 1992 to form the new Paris Convention) to adopting an ecosystem-based approach to environmental protection and management through its Annex V. OSPAR has no competence in fisheries, but the EU ***Common Fisheries Policy*** and the FAO ***Code of Responsible Fisheries*** also both refer to the Ecosystem Approach.

# 2. THE STRUCTURE & FUNCTIONING OF MARINE ECOSYSTEMS

## 2.1 Introduction to the Concepts

The understanding and management of ecosystems against a background of human activities and actual or potential degradation centres on knowledge of the structure and functioning of ecosystems, including both the non-biological and biotic parts, and the way in which they are affected by human activities. The term ***ecosystem functioning*** was regarded by Naeem *et al.* (2002) to refer to the activities, processes or properties of ecosystems that are affected by its biota. However, this definition seems to combine both structure and functioning and does not include the way the biota is influenced by the environmental variables. Because of this, this report separates ***ecosystem structure***, defined as indicating '*the components of the system'*, from ecosystem functioning. The concept of '*ecosystem functioning*' for the purposes of this report is regarded as:

> *The net result of rate* ***processes*** *within and between the physical, chemical, biological and anthropogenic components and influences in the ecosystem*

In this context, a process is regarded as a time-dependent action, i.e. a rate, which can be extrinsic (externally operating) or intrinsic (internally operating) to the biota. For example, the effects of climate-producing wave conditions which physically stress the organisms or the degree to which organisms obtain their necessary resources such as oxygen or food. The processes can be separated into the bottom-up processes, for example the provision of food consumed by predators and grazers, and the top-down controls or responses, for example predation by fish, seabirds and marine mammals, as well as the way in which the structural and functional components interlink. The present study indicates the way in which these processes act upon ecosystem structure.

The biological structure and processes can be defined as components and actions which occur either within or across a hierarchical set of ***levels of biological organisation***. Cellular and physiological processes occur within individuals and individuals exhibit behaviours. In turn, many individuals of the same species constitute a population; several populations of different species occurring together create an assemblage or community while many assemblages occurring within one area and the interactions within and between them and the physico-chemical environment constitute an ecosystem.

Within this overall framework it is necessary to consider that rate processes will occur over different time scales. For example, changes in primary production (i.e. the production of food by photosynthesis) will be detectable over very short timescales (e.g. minutes) whereas physiographic morphology (i.e. the shape of the coastline) changes over very long and even geological timescales (10,000s years). A number of approaches have been applied to the study of ecosystem functioning, and many of these have a strong relationship to scale (both in time and space). For instance, a recent Australian approach advocated by Butler *et al*. (2001) has used a decreasing hierarchical scale that ranged from provinces, through biomes, geomorphic units, primary biotopes, secondary biotopes, to biological facies. Similarly, De Jong (2000) indicates the spatial scales adopted by Dutch workers (see below).

In the Welsh context, it is important that the appropriate scale/approach be applied within the current study whereby the concepts are applied to ecosystems relevant to the Welsh coastline and as such, a middle level ***biogeomorphic unit*** may be relevant. Within this approach, and as required by CCW, these marine ecosystems have been divided into a series of units based upon a combination of biological and geomorphological parameters. These units have a characteristic and recognisable structure that can be cross-referenced to other management approaches such as those used by the Habitats Directive and ***Shoreline Management Plans (SMPs)***. The units chosen include: estuary, intertidal (open coast), subtidal (open coast) and pelagic, with the first three of these incorporating the sea bed (***substratum***) and the ***water column*** overlying the sea bed. It is important to note however, that these are relatively arbitrary units since realistically all of these areas are linked to one another in terms of the way in which the marine ecosystem functions. The terrestrial components such as sand dunes and saltmarsh have been incorporated into the respective estuarine or intertidal area. The importance of such biogeomorphic units then can be described within the context of ***ecosystem capital*** and goods and services, i.e. the particular ecosystem features that are important for natural functioning and human uses.

As indicated above, there are many initiatives to protect and enhance ***biodiversity*** which is defined as *the sum total and extent of genetic, taxonomic and ecological components over all spatial and temporal scales* (modified from Harper & Hawksworth, 1994 in Naeem *et al.*, 2002). While the way in which biodiversity influences ecological functioning has long been discussed in the terrestrial and microbial fields (e.g. references in Loreau *et al.*, 2002), this has only recently been discussed for the marine area and macrobiological aspects. This is defined as the '*ecosystem function – biodiversity debate*' (Naeem *et al.*, 2002). This debate appears to centre on two questions (modified and expanded from Mooney, 2002):

1. What is the influence of biodiversity on system processes such as nutrient cycling, primary and secondary production, over differing spatial and temporal scales and against a background of global change in climate, land use and species movements?, and

2. How are fundamental ecosystem responses such as stability, resilience and resistance affected by species diversity, again against a background of global change?

Emmerson and Huxham (2002) consider that most marine ecologists concentrate on either the effects of individual marine species on certain ecological processes, such as sediment disturbance (e.g. Mazik & Elliott, 2000) or on the gross measures of ecological processes by calculating budgets and fluxes, e.g. the movement of carbon through the system. This therefore indicates the importance on the system of functional groupings such as structural and ecosystem engineers. Further work is required to determine the influence of biodiversity on marine ecosystem functioning (Emmerson & Huxham, 2002) although this may be difficult in open marine systems where the exchange of materials and species between areas is much easier. Despite the above, an examination of the literature gives the impression that the ecosystem function – biodiversity debate is ecological semantics and is of less importance at the level of marine ecosystem management.

## 2.2 Ecosystem Concepts and Terminology

Prior to explaining the concepts of marine ecosystem functioning in greater detail, the most important terms are defined below.

### 2.2.1 ECOSYSTEM

An ***ecosystem*** can be defined as:

'*a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit*' (CBD, 2000).

This has been simplified slightly here as: '*a dynamic complex of plants, animals and micro-organisms and their environment interacting as a functional unit*'.

As a concept, an ecosystem can be at one of many spatial scales from the whole planet, through a regional sea down to a single rockpool and as such its understanding and functioning also have to be considered at those levels (Likens, 1992). Hence, the above definition then requires a spatial dimension, for example Likens (1992) regards it as a 'spatially explicit' unit in which all the abiotic and biotic processes occur within its boundaries. There is no widely accepted agreement by ecologists regarding the absolute size of that 'spatially explicit' unit and while an ecosystem can be small or large, the links between systems will influence its size. For example, while such a spatially-defined unit is more easily defined and discussed in relation to the land and terrestrial systems, this is not the case with unbounded aquatic marine systems and large freshwater systems in which the flow of materials and organisms is easier between different parts. Recent studies have indicated the links of scale between the way in which biodiversity affects ecosystem functioning but these have mostly been tested using microbial systems and as such are not yet applicable to the large organisms in marine ecology (Petchey *et al.*, 2002).

An ecosystem can be regarded as the net result of a set of sequential and interlinked components and processes in which the physico-chemical factors play a fundamental role as forcing variables. The ecosystem consists of a set of structural elements or components and then the pathways and transfer of material or energy flux between them create the rate processes which constitute ecosystem functioning. These somewhat abstract concepts are described and illustrated below. This framework can be expanded upon in terms of the inter-relationships, these are illustrated later in the report but are introduced here as:

a) '*environment-biology*' processes whereby the physico-chemical system and regimes create the fundamental niche for colonisation by the biological community;

b) '*biology-biology*' processes whereby the resultant biological community is modified by biological processes;

c) and '*biology-environment*' processes whereby the biota may modify and influence the physico-chemical system (the environmental regime);

d) finally, human influences then have the capability to modify each of these physical, chemical and biological systems.

This summary indicates the structure, functioning and processes in ecosystems but it is emphasised that these terms can relate to any of the levels of biological organisation (cell, individual, population, community or ecosystem).

### 2.2.2 LEVELS OF BIOLOGICAL ORGANISATION

In biological and ecological terms, it is necessary to consider the structural components and functioning processes which operate at all levels from the cell, through the individual, population, and community, up to the ecosystem level. These have been termed levels of complexity (Likens, 1992) and while it is argued that an ecosystem is more complex than a cell, the preferred term here is ***levels of biological organisation***. In this hierarchical system, processes and fluxes of material operate within and between these levels and the impact of human activities on the marine system also occurs at all levels (e.g. see McLusky & Elliott, 2004). Those structural components and functional processes taken together create what may be termed the ecological attributes of the ecosystem. In ecological terms, at their most fundamental the levels may be seen as an energy matrix (Table 1) but each level is nested within the higher levels. Some of the attributes, such as competition, occur throughout all levels but are included in Table 1 only under the most important. For example, competition can occur within and between cells just as between individuals and species, and invasion/extinction can be viewed as a population process as well as a community process.

**Table 1: Structure and functioning at different levels of biological organisation (modified and expanded from Likens, 1992)**

| Cell | Individual | Population | Community | Ecosystem |
|---|---|---|---|---|
| biochemical pathways | growth | recruitment as larvae/ juveniles | size and biomass spectra | system biomass |
| metabolism | reproduction | population age/size structure | diversity | system productivity |
| division | physiology | population growth rate | interspecific competition | energy flux |
| | behaviour | population viability | spatial structure | energy cycling |
| | food production/ feeding | population cycles | distributional patterns, e.g. zonation | nutrient flux and cycling |
| | somatic condition | rate of recruitment to adult population | succession | resilience/stability |
| | disease resistance | migration patterns | invasion/ extinction | |
| | mortality | spatial distribution | indirect competition/ mutualism | |
| | | intraspecific competition | predator/prey cycles | |

## The Structure of an Ecosystem

At its most basic, the structure of an ecosystem relates to the quantity and composition of the components in it at any one time. In more detail, ecosystem structure may be defined as '*the composition of the biological community including species, numbers, biomass, life history and distribution in space of populations; the quantity and distribution of the abiotic (non-living) materials such as nutrients, water, etc; the range, or gradient, of conditions of existence such as temperature, light etc.*' (Odum, 1962; Mathews *et al.*, 1982).

Using a modification of the approach suggested by Mathews *et al.* (1982), ecosystem structure can be separated into two sets of components - the ***abiotic*** attributes which encompass the environmental physico-chemical characteristics, such as substratum type which will influence benthic communities, and the ***biotic*** attributes, which relate to the presence of species (Table 2). Within this classification, certain attributes may fall into both the biotic and abiotic categories e.g. saltmarsh contains biological species (biotic) but also has a structural element with respect to coastal protection or forming a physical presence which encourages the development of other biota (abiotic). As a second example, a mussel bed is a biogenic reef composed of a species but it also creates hard substrata for other species to colonise.

The structure of a community or ecosystem can be determined and represented as one or more of 3 types of attribute (McLusky & Elliott, 2004). Firstly, and most commonly this is using a ***taxonomic approach*** in which all species are identified and the patterns between those species are determined. Secondly, ***size and/or biomass spectra*** may be determined in which the identities of organisms are less important than their role in the system as determined by their size or individual biomass. Finally, the latter idea is expanded by determining ***functional groups*** which combine species with similar ecological characteristics (e.g. Elliott & Dewailly, 1995). Hooper *et al.* (2002) discuss functional diversity compared to species diversity in ecosystems and suggests the former brings together species showing either similar <u>responses</u> to the environmental changes or having similar <u>effects</u> on the major ecosystem processes.

Raffaelli *et al.* (2002) emphasised the value of the functional group approach in understanding ecosystems given the difficulty of determining precisely the feeding behaviour of individual species. The term functional group is synonymous with functional type, guild, ecotrophic guild, ecological group and is most useful in determining the overall role of organisms irrespective of their taxonomic names, for example whether an organism is a bioengineer which modifies sediments or a major carnivore in depleting prey (Elliott & Dewailly, 1995).

## The Functioning of Ecosystems

At its most basic, the term 'functioning of ecosystems' describes the rate processes within and between the biological structural components, i.e. changes in any component with time and thus it may be regarded as the sum total of all the processes which occur within the system. In particular, this involves the transfer and cycling of energy and materials such as organic matter and nutrients, for example feeding and predator-prey relationships or the remineralisation of materials by the decomposers. The functioning of ecosystems incorporates the processes within individual populations such as recruitment, growth and mortality which combine to give the population dynamics of each species.

The functioning of ecosystems can be described as the merging of bottom-up and top-down processes. While there are many texts that describe marine food webs in detail, it is necessary here to indicate the main features of the ecosystem. For the bottom-up processes, the physico-chemical system will create a niche (the space or place in the ecosystem occupied by an organism) and influence the ability of individuals or species to occupy the niche, to acquire energy and to produce food/biomass. The latter biological production, either as gametes or body (somatic) material, will then increase the population size and biomass of a species and eventually provide material to the higher predators or the decomposer food chain. The upper levels of the system, the top predators which will include the groups of high conservation importance such as wading birds, fishes or marine mammals, will then exert population controls on the lower levels; hence the latter are regarded as top-down processes. In addition, any higher level influence on a lower level can also be viewed as a top-down control, e.g. suspension feeding by filter feeders will effect a control on phytoplankton, as will grazing by limpets on seaweed (Kaiser *et al.,* 2005).

Ecosystem functioning can therefore be seen to describe the major or higher level processes that occur within an ecosystem; where these lead to benefits for Man, such as the provision of food, then they are termed ‘ecosystem services’. In more detail, ecosystem functioning may be described as:

‘*the rate of biological flow through the system, that is, the rates of production and the rates of respiration of the populations and community; the rate of material and nutrient cycling, that is the biogeochemical cycles; biological or ecological regulation and for example, in photoperiodism) and regulation of environment by organisms (as, for example, in nitrogen fixation by microorganisms)*’ (Odum, 1962; Mathews *et al.*, 1982).

As with ecosystem structure, ecosystem functioning can be separated into two sets of components - the 'biotic' attributes, which relate to biological identities and the 'abiotic' attributes that encompass environmental physico-chemical parameters, such as erosion-deposition cycles of differing substrata that will influence benthic communities (Table 2). The biotic attributes include and are influenced by the population and community dynamics, for example changes in the presence of species, due to differing tolerances to changes in environmental variables, hence modifying community structure, and predator-prey relationships and recruitment rates. This hierarchical and complex system is the essence of the need for the Ecosystem Approach since the biotic and abiotic factors are closely interrelated and the functional interplay in a system is extremely complex.

**Table 2: Examples of ecosystem structure and functioning (modified from a concept by Mathews *et al.*, 1982)**

| Ecosystem: | | | |
|---|---|---|---|
| **Structure (i.e. attributes measured at one time)** | | **Functioning (i.e. a rate process)** | |
| **Abiotic** | **Biotic** | **Abiotic** | **Biotic** |
| *Examples*:<br>Temperature<br>Physiography<br>Grain size (sediment type) | *Examples*:<br>Species diversity<br>Species richness<br>Biomass<br>Amount of chlorophyll *a* | *Examples*:<br>Flushing rate<br>Heat flux<br>Residence time of a water mass in an estuary<br>Erosion-deposition cycles | *Examples*:<br>Annual change in diversity<br>Growth<br>Annual change in primary production |

## Processes in Ecosystems

As with ecosystem functioning, the term ‘ecosystem process’ implies an action and the incorporation of a rate change, i.e. a feature of the system that changes with time, and as such the terms may be regarded as being synonymous. Such processes will include any interactions that link organisms with each other and with their environment, for example, predation, mutualism, primary production, and nutrient cycling. An ecosystem function will normally be influenced by many processes occurring within the environment. For example, primary productivity is an important ecosystem function that is affected by processes determining light regime, nutrient supply and temperature as well as others. In general, the environmental processes will create and modify an organism’s environment and habitat and thereby many of the biological processes relate to an organism’s ability to utilise the available biological, physical and chemical resources; this leads to competition between organisms, within species (intra-specific/intra-population) and between species (inter-specific/inter-population) for available resources such as food, nutrients, light, space and reproductive partners/products. These concepts are discussed further below.

## Relationships Between Ecosystem Structure and Functioning

It is necessary to provide and expand upon the basic concepts whereby the structural and functional components interlink through a set of processes (Figure 1). These processes relate to the following inter-relationships between the environmental and biotic attributes:

- ‘*environment-biology*’ processes whereby the physico-chemical system (e.g. salinity, temperature, sediment, geology, hydrography, etc) creates the fundamental niche for colonisation by organisms; for example, reduced water currents will allow the development of muddy substrata which will be colonised by deposit-feeding organisms; biogeographic regimes and physico-chemical oceanographic processes and gradients will thus create the conditions likely to be colonised by organisms;

- '*biology-biology*' processes whereby the resultant community is modified by biological processes and interactions such as predator-prey relationships, competition, and recruitment processes such as propagule supply and settlement; for example the mud-dwelling invertebrates then compete with each other for space but also provide food for wading birds and fishes;
- and '*biology-environment*' processes whereby the biology may influence the physico-chemical system and the import and export of materials into and out of the system; for example, benthic invertebrates bioturbate and alter the sedimentary regime leading to chemical changes, or the oxygen demand created by a large number of organisms occurring together.

The sum total of these interlinked processes therefore creates the observed ecosystem. In turn, anthropogenic change and distortions to the natural system caused by human uses are then superimposed on this set of fundamental relationships. These interlinked processes are shown as a conceptual model in Figure 1.

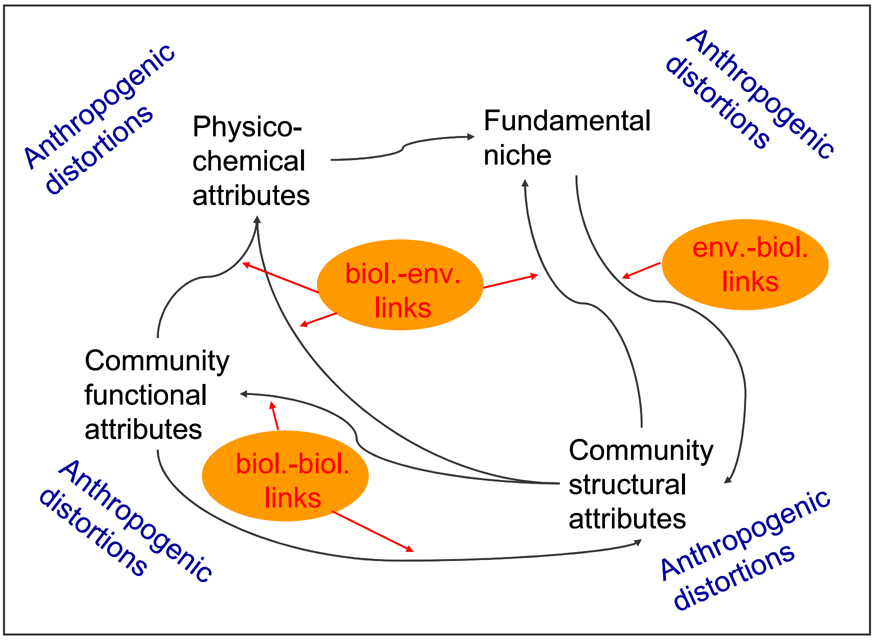


**Figure 1: A schematic diagram indicating linking and feedback between environmental and biotic marine/estuarine attributes**

This framework is not dissimilar from that of Hawkins (2004) and as such leads to the links between marine biodiversity links and the many other factors which determine and influence ecosystem functioning in marine, coastal and estuarine systems. He emphasises that the openness of marine systems therefore is of importance in determining the boundary conditions (or lack of them). Hence the influence of biota on the system may be in the near or far field given the openness and transport of biological, physical and chemical materials.

The physico-chemical attributes of the marine environment are a set of inter-linked regimes which can be loosely grouped to produce, at its most fundamental, the water column fundamental niche and the substratum (seabed, intertidal surface) fundamental niche which are then occupied by organisms (Figure 2). For example, the global position of a site and its prevailing climate will influence the regimes relating the wind and hence waves, the tides and hence exposure, the water run-off and hence hydrographical conditions and salinity. The red boxes in Figure 2 emphasise the large number of oceanographic regimes which comprise the marine environment whereas the white boxes are those factors which create or influence those regimes. The links between the many attributes result in the two main marine fundamental and overarching niches – for the water column and substratum (representing the left and right parts of the diagram respectively). By the nature of the marine environment, these interlinks are complex as shown by Figure 2 which indicates the way these marine physical and chemical attributes interact and influence each other and, by extension, are adversely affected by knock-on effects between the variables. It is emphasised here that an understanding of these regimes is fundamental to interpreting and understanding the biological nature of the ecosystem and the way in which Man affects that nature.

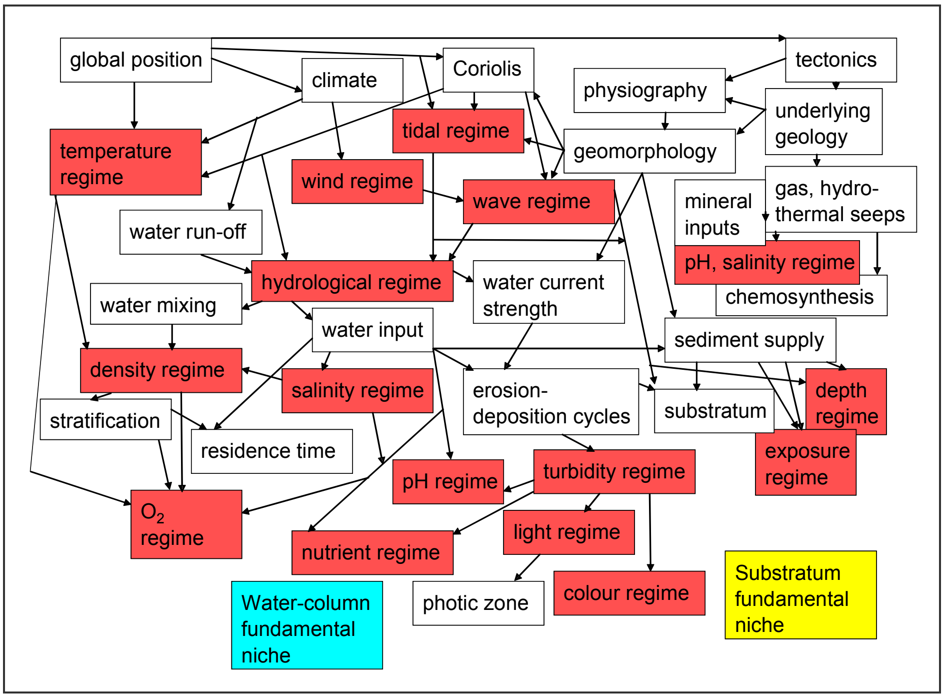


**Figure 2: The links between the physico-chemical attributes resulting in the two main marine fundamental and overarching niches – for the water column and substratum.**

The integration of processes between the water-column and the substratum is critical and constitutes each ecosystem, for example an estuary, coastal embayment, seagrass bed, etc. Once the fundamental niche has been produced then the basic biological community will develop according to the preferences and tolerances of the organisms to the environmental conditions occurring in any one place. For example, once a salinity regime has been created then only those species tolerant of that regime will occupy that niche so that in an estuary, upper estuarine communities dominated by ***euryhaline*** (wide salinity tolerance) forms will gradually transform into communities dominated by predominantly ***stenohaline*** (narrow salinity tolerance) forms near the estuary's mouth. Some of the environmental factors will create discrete areas and thus the accompanying discrete communities, for example a rocky substratum will maintain a fundamentally different community from an adjacent sandbank due to the inherent stability of bedrock compared with mobile sand. As long as there is a suitable light regime, a rocky area will be dominated by macroalgae which can be controlled by the resultant grazing animals such as limpets and winkles. If such a rocky area is below the depth for sufficient light penetration or if water is so turbid, as in the turbidity maximum region of many estuaries, that light cannot penetrate, then attached primary producers such as macroalgae will not develop. In contrast, a sandy seabed will be dependent on inorganic and organic matter conveyed by currents and will be populated by animals tolerant of mobile substratum that can utilise organic matter. However, although such widely differing habitats exist, in most cases, especially near the shore and within estuarine areas, continua will be created thus yielding communities that gradually merge with others.

As introduced above, the ***ecological niche*** is the fundamental area that can be occupied successfully by an organism. This includes the appropriate medium, e.g. water column or sediment, with the required degree of protection and appropriate food or materials for producing food. ***Niche breadth*** indicates the range of environmental conditions suitable for occupation by a species. For example, a fish species such as whiting which moves over the seabed will be tolerant to many bed types and thus have a broad niche whereas a species such as the honeycomb worm *Sabellaria* will have a narrow niche in terms of the type of substratum that it can occupy. Similarly, a species that is generalist or opportunistic in its feeding and takes whatever prey it encounters has a wide niche breadth whereas a specialised feeder has a narrow niche. Niche breadth then can be regarded as combining ***habitat occupation*** and ***ecological range*** which respectively refer to the different physical areas in which an organism can occur and the overall geographical area covered by the species. ***Niche overlap*** occurs when two organisms require the same conditions, food type, etc. and as such may lead to competition between species (interspecific) or within a species (intraspecific); the competition can then be minimised by niche separation in space or time, for example where organisms feed in different places or at different times. ***Niche complementarity*** occurs where organisms have non-overlapping but complementary niches (Naeem *et al.*, 2002), for example the vertical separation in sandy sediments shown by the deep burrowing razor shells *Ensis* and the shallow burrowing amphipod *Haustorius*.

Most marine biological food webs have a well-defined and classical structure of primary producers (e.g. seaweeds) leading to primary consumers (e.g. grazers), secondary consumers (e.g. predatory crabs), etc. This system will be produced as the result of the biological inter-relationships such as predator-prey interactions, competition and recruitment processes (Figure 3). Higher trophic levels, such as birds and fishes, will exert a population control on the lower tiers during predation. In addition, material, whether from death, exuvia (excreted material) or predation, will fuel the detritus/decomposer food chain in which the microbial loop (bacteria, fungi, protozoans) will remineralise materials thus adding them to the system for re-use.

Figure 3 indicates that competition is a main influence operating both within (green arrows) and between (yellow arrows) the different trophic levels. There are generally three resources that are required by organisms for functioning: (1) food, (2) space and (3) 'mates' (where the latter refers to sexual products and/or partners). The components of the communities will exert competition for available resources such as food, space or available reproductive partners. ***Resource partitioning*** will occur if there is any competition for these and that competition can be within or between species. Competition between mobile species is often for food whereas competition between sedentary species is often for space. For example, if marine mussels and barnacles occupy a rocky shore then they will compete for the available space. Mechanisms or strategies for reducing inter- or intra-specific competition can lead to resource partitioning, for example different-sized fishes of the same species taking different prey (ontogenetic selection) (Elliott & Hemingway, 2002) or different wading bird species feeding on an intertidal area at different times of the year.

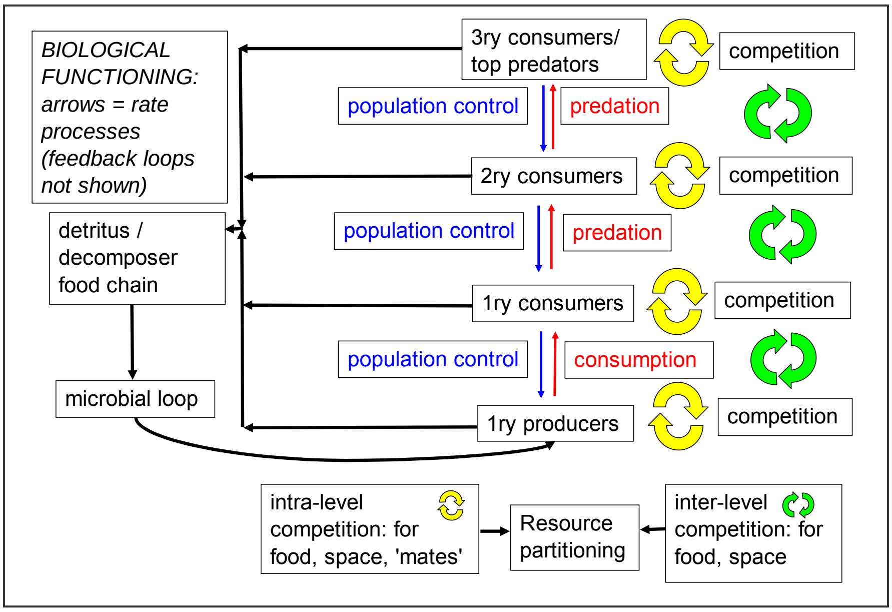


**Figure 3: A summary of functioning within the biological elements of an ecosystem**

### 2.1.3 Ecosystem Condition (Health)

The terms 'health' and 'damage' relate to the well-being of a system and its ability to carry out a set of functions and, in the present context, relate to biological well-being, whether that biology relates to the natural system or to Man. At its most basic, the terms relate to a fitness for survival hence incorporating both acute and chronic degradation but they also relate to a fitness for purpose (once the purpose of the system has been defined). This therefore illustrates the importance of defining and where possible quantifying ecosystem goods and services which by definition are impaired in an unhealthy or degraded ecosystem. As human activities, again in the context of the present report, will be responsible for that degradation then society chooses *de facto* to impair the ecosystem and thus has control over its recovery. For example, society can decide whether sewage should be discharged into the sea and whether the cost of treatment and remediation should be spent. The socio-economic aspects of habitat protection and restoration is discussed later in this report.

A healthy ecosystem will be a system that encompasses all necessary functions and has the components commensurate with the prevailing physico-chemical regime. It has the capability to resist, or recover from, disturbance and is thus regarded as being resilient (Defra, 2004b). It will have all the expected components of the ecosystem and the expected linkages between such components. Similarly, an unhealthy or degraded ecosystem is lacking in one or more of these features. In determining the health and well-being of the marine system, in addressing the causes of any deterioration in ecosystem health and in re-creating healthy systems, parallels can be drawn with the terminology used by the medical fields (Table 3). An assessment of change from a perceived normal situation can be followed by a prediction of the direction in which ecosystem change progresses if human influences are not removed, thus allowing causes of change to be mediated, mitigated or compensated (from Elliott & Cutts, 2004; see also Steevens *et al.*, 2001). Of course, actions to prevent adverse change are the most important aspect of marine environmental management.

**Table 3: Comparison of the health of medical and environmental systems (*1 Modified from Steevens *et al.*, 2001; Elliott & Cutts, 2004; *2 using an extension of symptoms for the diagnosis of ecosystem pathology - see text)**

| Determination of unhealthy systems | | |
|---|---|---|
| **Medical (*1)** | | **Environmental** |
| Diagnosis | = | Assessment (*2) |
| Prognosis | = | Prediction |
| Treatment | = | Remediation / Creation |
| Recovery | = | Recovery / Restoration |
| Prevention | = | Prevention |

There are a few well-defined categories of changes to ecosystems as the result of human activities which, again following the medical analogy, in general can be reduced to a set of seven ***symptoms of ecosystem pathology***, i.e. adverse changes to the system (Box 3). A deviation in any of those symptoms, from an optimum that would be regarded as necessary for the healthy functioning of an ecosystem, indicates a reduction in health of a system. As a management and monitoring tool, any of these symptoms can be regarded as an indicator of adverse change. Some of these features relate to the ecosystem functioning whereas others modify the degree of biodiversity in the system.

**Box 3: The seven symptoms of ecosystem pathology (modified from Harding, 1992, and McLusky & Elliott, 2004)**

1) the fate and effects of nutrients, e.g. the increase in concentration as the result of increased diffuse and point source discharges but also as the cause of eutrophication (an over-enhanced productive capacity);
2) primary production, e.g. the organic production of a system which may be over-stimulated through increased sewage inputs adding nutrients to the system, or depressed by the presence of turbid water which will reduce the light regime required for photosynthesis;
3) species diversity, e.g. the removal of species which are intolerant of change under stressful conditions and the encouragement of stress-tolerant species; the introduction of alien or invasive species;
4) community instability (biotic composition), e.g. the increase in biological turnover due to the dynamics of stress-tolerant species;
5) size and biomass spectrum, e.g. the tendency towards smaller, *r*-strategist (usually small-bodied) organisms under stressed conditions;
6) disease/anomaly prevalence, e.g. the reduced tolerance of organisms to infection and the development of pathological anomalies such as ulcers when placed under stress;
7) contaminant uptake and response, e.g. the increased accumulation of conservative contaminants, such as trace metals, and perhaps the production of detoxification or excretion mechanisms after exposure in order to remove toxicants from the system.

Indicators of health may be identified at one or more of the levels of biological organisation; from cellular processes, through whole organisms, populations, communities and finally through to ecosystems (Lawrence & Hemingway, 2003; McLusky & Elliott, 2004). The speed of response to the same amount/magnitude of any stressor decreases with a progression up these levels or requires a greater magnitude of stress to bring about a response. For example, while exposure to a toxic metal such as mercury will adversely affect a cell within seconds to minutes, it will take much longer or require a much higher dose to affect communities and ecosystems. In contrast, biological complexity increases with a progression through these levels of biological organisation - i.e. the ecosystem is inherently more complex than the cell. A more complex system may be more resilient to change because it will have greater redundancy conferred by the sum of its many components and the array of interactions among these (see Section 3 Recovery). For example, it is possible that a highly complex and variable system such as an estuary will absorb a degree of stress and therefore a higher level of stress will be required before adverse changes take place or are detectable at the ecosystem level.

There have been many approaches to the assessment of ecosystem condition (health) and these have been summarised in Defra's *Understanding of undesirable disturbance… Stage 1 Report* (Defra, 2004b). A brief summary of these approaches with key references is provided below (Table 4). It is of note that health can be assessed at different levels of biological organisation, from the health of a cell to the health of an ecosystem. A summary of the various levels of health assessment is given in Table 5 (Defra, 2004b). Thus there is an intimate link between these concepts and those relating to adverse impacts which can be defined as the reduction in fitness for survival by any of the biological levels of organisation (McLusky & Elliott, 2004).

**Table 4: Concepts Relevant to the assessment of Ecosystem Condition (Health) (modified from Defra, 2004b)**

| Concepts | Definition | Example references |
|---|---|---|
| Ecosystem health | Relates to the normal state and successful functioning of the system | Costanza *et al.*, 1992<br>Costanza & Mageau, 1999 |
| Ecosystem integrity | Relates to how pristine or undisturbed a system might be; the ability to maintain its organisation | Kay, 1991<br>Jørgensen, 1997<br>Müller *et al.*, 2000<br>Campbell, 2000 |
| Ecosystem quality | Condition of a particular ecosystem, measured in relation to each of its intended uses; it is usually assessed in relation to established guidelines, objectives and indicators set by relevant agencies. Relates to chemical, physical and biological aspects. | Harding, 1992 |
| Ecosystem pathology | Relates to the symptoms which indicate departure from normality (healthy state?); reflects a decrease in fitness-to-survive | Rapport, 1998; Harding 1992. |
| Ecosystem distress | Relates to the state of less than good health and a decreasing fitness-to-survive; reflects a system reacting to change, functioning under stress or showing departure from normality | Rapport, 1995<br>Rapport *et al.*, 1998 |
| Ecosystem dysfunction | Relates to the state of less than good health and poor fitness-to-survive; not functioning or functioning in a disturbed manner | Rapport, 1995 |
| Ecosystem morbidity | Relates to a state of less than good health – showing signs of 'sickness' and low survival potential | Sherman, 2000 |

**Table 5: Assessment of health at different levels of biological organisation (modified and expanded from Lawrence & Hemingway, 2003; Defra, 2004b)**

| Level | Assessment of health |
|---|---|
| Cell | Biochemical functioning, as the maintenance of cellular processes; or the maintenance of cell structure such as the integrity of the organelles; for example, cells have an ability to detoxify certain pollutants within organelles such as lysosomes; however, cellular health will be compromised if there is the induction of detoxification mechanisms following pollutant exposure or the result of the release of metabolising enzymes as the result of lysosomal degradation. |
| Individual | Functioning in terms of physiology, behaviour and structural health e.g. anatomy and morphology; changes in any of these will impair performance and thus lead to a reduction in an organism's fitness to survive, grow and reproduce. For example, an exposure of dogwhelks to the antifouling paint TriButyl Tin will result in imposex and the inability of female dogwhelks to reproduce. |
| Population | Reflected in the sustainability and maintenance of the population, in terms of growth, behaviour and reproduction by the individuals; hence the need to determine any reduction in the fitness for population survival and an ability to compete in the community; these changes may be reflected in the sizes and thus ages present in the population. For example, larvae and juvenile stages are more susceptible to pollutants than are more resistant adults and thus exposure to pollution may reduce the number of recruits coming into a population. |
| Community | Reflected in the maintenance of an appropriate assemblage (the combination of species present) which reflects the physico-chemical conditions and functions as expected, to allow the maintenance of the relationships between different species (including interspecific relationships e.g. competition and predator-prey); a loss of community health is thus shown by a changed community (species) diversity, size and biomass spectra and complement of functional groups. |
| Ecosystem | Reflected by a combination of appropriate structure, functioning and an ability to withstand disturbance. |

## 2.3 Critical and Fundamental Marine Processes, their Scales and the Welsh Context

### 2.3.1 Critical and Fundamental Processes

The functioning of ecosystems incorporates a very large number of contributing processes. For example, primary production is a consequence of photosynthetic processes comprising energy processes such as light capture, photolysis, electron transport and energy production. Not all of the energy captured contributes to production as some is lost to other processes (e.g. fluorescence, respiration, heat dissipation).

Given the complexity of the marine environment, it is not within the scope of the present report to address all of the processes that are known to occur within the coastal and marine environment but merely to develop a list of the relevant critical/fundamental marine processes and summarise the influence of anthropogenic change on those processes. These processes can be divided hierarchically into 4 types of processes: level 1 ('physico-chemical'), level 2 ('biological inter-relationships and mediation'), level 3 ('anthropogenic influences'), and level 4 ('responses to change') (Table 6a-d). The first two level processes influence the creation of biological habitats and the community structure and function and so can be regarded respectively as drivers and responses to those drivers. In contrast, the third level processes are those which should be prevented otherwise there will be a reduction of the biological health of the system. Finally, the fourth level processes are those mechanisms required to enable an ecosystem to recover, or to restore itself or its components but within the sustainable use of the ecosystem and its services. (The anthropogenic processes and responses are discussed further in the latter sections of this report). It is of note that a process can imply either an action taking place, e.g. the wave climate is sufficient to create exposure zones, or even an action is not occurring which then creates a different status, e.g. no mixing of waters which creates stratification in the water column.

**Table 6: Critical/Fundamental Marine Processes**

| **(a) Level 1: Physico-chemical Processes** | |
|---|---|
| **Process:** | **Specific regions to which the process applies** |
| wind regime leading to the wave and swell regime creating the exposure regime. | primarily open coastal areas |
| unrestricted wave energy to structure the shore exposure regimes | primarily open coastal areas |
| water flow/runoff creating the salinity regime/ maintenance of salinity regime | primarily estuarine areas |
| appropriate temperature regime | all areas |
| lack of mixing creating the stratification regime | primarily restricted to exchange waters |
| sediment to intertidal and subtidal areas | primarily sedimenting areas inshore and in estuaries |
| suitable (biological) substratum | all areas |
| photic zone/light regime for primary producers | primarily clear (less turbid) coastal areas |
| production of favourable water quality for nektonic migration | primarily estuarine migration routes |
| supply of oxygenated water | primarily waters of restricted exchange and/or organic enrichment |
| an uninterrupted flow creating the tidal regime | primarily estuarine areas |
| sediment capture and retention | primarily estuarine areas |
| energy dissipation coastal protection | primarily open coastal areas |
| habitat maintenance | all areas |
| dispersal of **propagules** through water exchange/currents | all areas |
| natural disturbance (scour, storm action, grazing, bioturbation) | all areas |

**Table 6 contd: Critical/Fundamental Marine Processes**

| **(b) Level 2: Ecological Processes – biological inter-relationships and mediation** | |
|---|---|
| **Processes:** | **Ecosystems to which it applies** |
| conditions for carbon fixation (autochthonous production) | primary producing bed areas (saltmarshes, seagrass beds, rocky shores, etc), water column |
| nutrient sequestration in sediments | primarily muddy intertidal sediments |
| nutrient levels for primary production | water column |
| primary production of material for primary consumers | all producing areas |
| net organic production/degradation creating oxygen regime | within water column and bed sediments |
| biomodification of sediments by fauna/flora (biostabilisation, bioturbation, bioengineers) | primarily intertidal muddy sediments |
| detrital processing and the delivery of detritus for decomposer food chain (allochthonous inputs) | primarily estuarine and inshore areas |
| delivery of recruiting organisms to an area | all areas |
| net settlement patterns creating competition | all areas |
| supply of food/nutrients to higher consumers | primarily important feeding areas such as mudflats and subtidal sandbanks |
| removal of waste products | all areas |
| critical internal (within/between an organism or community) processes (reproductive ability, disease resistance, predator defence, damage repair, growth). | all areas |

**Table 6 contd: Critical/Fundamental Marine Processes**

| **(c) Level 3: Anthropogenic influences on physico-chemical-biological processes** | |
|---|---|
| **Process:** | **General examples:** |
| water quality creating barriers to migration | e.g. input of oxygen-demanding wastes such as sewage into estuaries |
| physical barriers to migrations/dispersal | e.g. presence of weirs and amenity barrages in estuaries |
| estuarine, coastal and offshore structures creating hydrographic distortions | e.g. offshore wave, tidal and wind energy devices |
| polluting inputs creating contamination/pollution responses | e.g. industrial discharges |
| hydrographic and nutrient conditions creating eutrophication | e.g. diffuse run-off from agriculture and point source sewage discharges into waters of restricted exchange |
| organic enrichment creating community and size-spectral response | e.g. paper mill waste, sewage discharges and late-stage oil from spillages |
| removal of size classes of biota and/or species creating community imbalance | e.g. fishing and shell-fisheries targeting certain species and/or removing bycatch |
| removal of a population or increase of cultured species reducing genetic diversity | e.g. by fishing and aquaculture escapees respectively |
| input of alien and introduced species | e.g. by transferral in ballast water or the creation of new niches for colonisation such as hard bottoms in soft sediment areas |
| loss of seabed/wetland reducing biological productivity | e.g. land claim in estuaries or building infrastructure on the seabed |
| removal of prey populations and carrying capacity | e.g. loss of wetland and intertidal flats through land claim or hydrographical modifications due to barrage construction |

**Table 6 contd: Critical/Fundamental Marine Processes**

| **(d) Level 4: Management Processes as Responses to Change** | |
|---|---|
| Process: | Example: |
| Removal/remediation of contaminated areas of disused structures | e.g. pipelines, cables |
| Coastal protection - soft engineering | e.g. creation of habitat, managed realignment, beach nourishment |
| Coastal protection - hard engineering | e.g. seawall building |
| Waste minimisation and waste treatment | e.g. primary, secondary, tertiary |
| Exclusion zones and statutory limits to physical resource utilisation | e.g. shipping lanes, offshore energy, aggregates |
| Exclusion zones and statutory limits to biological resource utilisation | e.g. shellfish, fisheries |
| Habitat restoration, creation, replacement | e.g. managed realignment, beach nourishment, beneficial use of dredged material |
| Compensation of:<br>(i) users<br>(ii) resource<br>(iii) habitats | e.g.<br>(i) fishermen<br>(ii) restocking of fish and shellfish<br>(iii) creation of habitats |
| Barrier removal:<br>(i) water quality<br>(ii) physical structures | e.g.<br>(i) re-aeration, removal of inputs<br>(ii) dams, estuarine barriers |

At a more detailed level, there are processes internal to any biological level of organisation, such as biochemical and physiological aspects, competition and material fluxes, which are implicit in enabling ecosystems to function (e.g. Likens, 1992, and see Table 1 above). The promotion and completion of these will enable healthy individuals, populations, communities and ecosystems to be maintained. These intrinsic processes are not normally included as part of system analysis at a functional level, but may be required for consideration in greater detail under specific management scenarios. For example, at a functional level, the influence of the anti-fouling paint Tri-Butyl-Tin (TBT) would be noticed where the effect was sufficiently advanced (by the failed reproduction of gastropod molluscs such as dogwhelks) to alter the structure and function of the intertidal zone, e.g. following the removal of a population control by dogwhelks on the local barnacle population. However, at an earlier stage, where the TBT has produced some sterility in dogwhelks but this has not yet become sufficiently severe to be reflected at the population and community levels, its detection requires more subtle analysis. Hence, the detection of change under the implementation of the Ecosystem Approach requires analyses at the individual, population, community and ecosystem levels.

#### 2.3.2 SCALES AT WHICH MARINE FUNCTIONING OPERATES

The highly dynamic nature of the marine environment, in contrast to terrestrial systems and to a greater extent than in freshwater systems, dictates that some ecosystem processes may operate over large spatial scales; other processes may operate over very localised spatial scales. Management must therefore be considered at the scale most appropriate to the process. The particular scale may be dependent on the mobility of the organism or its dispersal stages; for example, cetaceans may operate at an NE Atlantic level whereas a population of brood-producing amphipods will operate within a small sedimentary area. The largest scale is ecoregions or biogeographical regions such as Boreal, Atlantic, Lusitanian, etc. whereby the dominant structuring force for invertebrates and marine plants, may be their temperature tolerances.

Ecosystems can operate at a number of spatial scales hence the difficulty faced by ecologists in identifying the spatial extent of an ecosystem and appropriate spatial management units. In Australia, one approach to categorising the various scales of an ecosystem which emphasises the geological or sedimentary control has been suggested by Butler *et al*. (2001):

- *Provinces*: based upon broad-scale geological patterns and 1000s of km in extent e.g. continental blocks and abyssal basins.
- *Biomes*: nested within provinces and at a regional (100s of km) scale, which show broad-scale geomorphology, e.g. coast, continental shelf, slope and abyssal plain.
- *Geomorphic units*: within each Biome at the local (10s of km) scale, are areas of similar seabed geomorphology and which usually have distinct biotas, e.g. seamounts, canyons, rocky banks, and coral reefs.
- *Primary biotopes*: are soft, hard, and mixed substratum-based units, together with their associated biological communities also at a local scale (10s of km).
- *Secondary biotopes*: are substructural units within primary biotopes that are distinguished by the types of physical or biological substrata within soft, hard, or mixed types at the site (<10km) scale, e.g. limestone, granites, shelly sands, or seagrasses.
- *Biological facies*: are site (<10km) scale units defined by a biological indicator, such as a species of seagrass, or group of hard corals, sponges, or other macrofauna linked to the facies.

In the Netherlands, De Jong (2000) suggested a similar approach which emphasises the spatial scale as being the primary factor, with higher scaled eco levels including a number of lower scaled eco levels and differing elements (Table 7).

**Table 7: Suggested scales of an ecosystem (De Jong, 2000)**

| | Indicative Mapping Scale | Basic Mapping Unit |
|---|---|---|
| Eco zone | 1:>50,000,000 | >62,500 $km^2$ |
| Eco province | 1:10,000,000-50,000,0000 | 2,500-62,500 $km^2$ |
| Eco region | 1:2,000,000-10,000,000 | 100-2,500 $km^2$ |
| Eco district | 1:500,000-2,000,000 | 625-10,000 ha |
| Eco section | 1:100,000-500,000 | 25-625 ha |
| Eco series | 1:25,000-100,000 | 1.5-25 ha |
| Eco tope | 1:5,000-25,000 | 0.25-1.5 ha |
| Eco element | 1:<5,000 | <0.25 ha |

The ecosystem management unit may be a geographical unit with recognisable biological characteristics, for example a coastal sediment cell, a seagrass bed, a saltmarsh, or an estuary, or it may be a larger interlinked area such as a regional sea. The management of geographical areas such as estuaries which include many different habitats may have to be through the management of those individual habitats. However, it is emphasised that management will have to reflect the different spatial scales, i.e. while the management of a seagrass bed can concentrate on the immediate area, thus suggesting a relatively self-contained ecosystem, the management of an SPA for overwintering migratory birds has to take account of events at areas outside the SPA used by the birds, for example for breeding (Stillman *et al.,* 2005). Similarly, other highly mobile organisms such as the fishes and cetaceans will use one ecosystem for part of the time and then another for the remainder, a feature particularly important in the open sea - estuarine - freshwater continuum (Elliott & Hemingway, 2002). Similarly, species will rely on different marine areas at different times, for example, rays may feed on subtidal sandbanks but then migrate outwards to other areas where they rest or reproduce.

While coastal, semi-enclosed and fringing habitats may be suitable management units, the open marine system has less defined boundaries and thus the influences by organisms and on organisms require to be considered over greater scales (Hawkins, 2004). For example, open coastal and marine systems may be influenced by the import and exchange of physico-chemical materials and by the exchange of reproductive products and recruits between populations over large scales (Giller *et al.,* 2004). In particular, organic material produced at one site may be used at large distances from that site (Hawkins, 2004). Because of this, in the Welsh context, there is the need to consider the appropriate scales for both assessment and management. These can be at the level of the whole coast, together with the inshore waters, thus the management to the 12 mile limit or, for nature conservation designations and the implementation of the EC Habitats Directive to the mid line in the Irish Sea. Furthermore, while the EC Water Framework Directive requires management of the impacts and pressures to ensure Good Ecological Status to 1nm from the baseline, the proposed EC Marine Framework Directive is suggesting control from the baseline (the recognised coastline). By building on the BioMor project (Mackie *et al.*, 1995) which mapped the subtidal biotopes and habitats, the Irish Sea Pilot Project mapped the marine landscapes for the regional sea area and then Boyes *et al.* (2005) mapped the permitted activities over these in order to produce a proposed zonation scheme. Similarly, the intertidal biotope maps produced by CCW for the Welsh coastline provide information at the 5m square scale about the basic biological units. Finally, the use of sedimentary cells as geomorphological-hydrological systems for the Shoreline Management Plans gives a further scale discrimination which is most suitable for coastal protection and flood defence.

### 2.3.3 ECOSYSTEM FUNCTIONING AND CHANGE IN A WELSH CONTEXT

The marine and estuarine environment can be regarded as a single ecosystem or divided into many component ecosystems. Although it is recognised that other ecosystem categories might be applied, by agreement with CCW, the present report focuses on the following four component ecosystems – the estuary, intertidal (open coast), subtidal (open coast), and pelagic (water column). However, it is emphasised that the first three of these only operate as an ecosystem by having both bed and water column components interlinked. For example, the functioning of seaweeds in intertidal areas requires a substratum for attachment and a water column for the successful completion of photosynthesis. Furthermore, the functioning of an estuary (and some bays e.g. Liverpool Bay) is intimately linked to that of the freshwater catchment and thus also to the adjacent terrestrial environment. It is also linked to the open coastal areas and the higher latitude areas which are respectively necessary for the populations of the juvenile fishes using the estuaries as nursery grounds and the overwintering wading birds using the estuary as a feeding area during southern migrations.

The role of the dominant and critical marine and estuarine processes identified above can be related to these 4 ecosystems (Table 8a-c). As is expected, while the level 1 (physical-chemical) processes differ in their importance slightly between the ecosystems, the level 2 (biological) processes almost all apply to all ecosystems. For example, the relationship between the riverine runoff and salinity is important for the functioning of an estuary but of little importance in open coastal areas. In contrast, the requirement of primary producers for nutrients to effect primary production occurs in all areas. This partly reflects a lack of discriminating ability amongst the ecosystems chosen but also reflects the critical importance of those processes to all marine areas.

The importance of the level 3 processes will reflect the ability of any area to support human activities. For example, the loss and conversion of wetland to be used for agriculture or industry is common in many estuaries and the input of polluting discharges is common to all licensed industries. Following these processes, the level 4 processes as defined here include the responses to human activities and their impacts (see Table 13 in Section 3.4.2). For example, the creation or rehabilitation of habitats is required following a certain level of deterioration.

**Table 8a: Level 1 processes (physico-chemical) within the chosen ecosystems**

| Process | Ecosystem | | | |
|---|---|---|---|---|
| | **Estuary** | **Intertidal** | **Subtidal** | **Pelagic** |
| Wind climate creating exposure regime | Yellow (red circle) | Orange (red circle) | Yellow (red circle) | Yellow |
| Allowing unrestricted wave energy to structure shore exposure regimes | Yellow | Red | Yellow | Yellow |
| Water flow / run-off creating salinity regime / maintenance of salinity regime | Red | Orange | Yellow | Yellow |
| Maintaining appropriate temperature regime | Yellow | Yellow | Orange | Orange |
| Delivery of sediment to intertidal and subtidal area | Red | Red | Orange (red circle) | Yellow |
| Maintenance of suitable (biological) substratum | Red | Red | Red | Yellow |
| Maintenance of photic zone / light regime for primary producers | Orange | Yellow | Orange | Orange |
| Production of favourable water quality for migration | Red | Yellow | Orange | Red |
| Ensuring supply of oxygenated water | Red | Red | Red | Red |
| Ensuring uninterrupted flow creating tidal regime | Red | Yellow | Yellow | Yellow |
| Maintaining sediment capture and retention | Red | Red | Orange (red circle) | Yellow |
| Maintaining energy dissipation / coastal protection | Red | Orange | Yellow (orange circle) | Yellow |
| Habitat maintenance | ? | ? | ? | ? |
| Ensuring dispersal of propagules (water exchange / currents) | Red | Red | Red | Red |
| Permitting natural disturbance (scour, storm action, grazing, bioturbation) | ? | ? | ? | Yellow |

Red = high importance, Orange = medium importance, Yellow = low importance

Circles represent that there are certain habitats within the ecosystem type where the process is either more or less important

**Table 8b: Level 2 processes (biological relationships & mediation) within the chosen ecosystems**

| Process | Ecosystem | | | |
|---|---|---|---|---|
| | Estuary | Intertidal | Subtidal | Pelagic |
| Carbon fixation | | | | |
| Nutrient sequestration | | | | |
| Maintenance of nutrient levels for production | | | | |
| Maintaining primary production of material for primary consumers | | | | |
| Net maintenance of organic production / degradation creating oxygen regime | | | | |
| Ensuring biomodification of sediments by fauna / flora (biostabilisation / bioturbation) | | | | |
| Maintaining detrital processes | | | | |
| Ensuring delivery of recruiting organisms to an area | | | | |
| Protection of net settlement patterns creating competition | | | | |
| Ensuring supply of food / nutrients to higher consumers | | | | |
| Ensuring removal of waste products | | | | |
| Maintaining critical internal processes (reproductive ability, damage repair, growth etc.) | | | | |

Red = high importance, Orange = medium importance, Yellow = low importance

Circles represent that there are certain habitats within the ecosystem type where the process is either more or less important

**Table 8c: Level 3 processes (potential anthropogenic influences) within the chosen ecosystems**

| Process | Ecosystem | | | |
|---|---|---|---|---|
| | Estuary | Intertidal | Subtidal | Pelagic |
| Water quality creating barriers to migration / dispersal | Red | Yellow | Orange | Red |
| Physical barriers to migration / dispersal | Red | Yellow | Orange | Orange |
| Polluting inputs creating contamination / pollution responses | Red | Red | Orange | Orange |
| Hydrographic and nutrient conditions creating eutrophication | Red | Red | Yellow | Orange |
| Organic enrichment creating community and size-spectral response | Red | Red | Red | Red |
| Removal of sizes and / or species creating community imbalance | Red | Red | Red | Red |
| Removal of species reducing genetic diversity | Orange | Orange | Orange | Orange |
| Input of alien and introduced species | Red | Red | Red | Red |
| Loss of seabed / wetland reducing biological productivity | Red | Red | Red | Yellow |
| Removal of prey populations and carrying capacity | Red | Red | Red | Red |

Red = high importance, Orange = medium importance, Yellow = low importance

Circles represent that there are certain habitats within the ecosystem type where the process is either more or less important

### 2.3.4 Relative Importance of Processes in Relation to Ecosystem Type

The maintenance of all habitats is dependent on the supply of oxygenated waters, the successful dispersion of larvae, especially given the planktonic spawning by most marine organisms, the ability to obtain nutrients and sequester carbon, the passage of material from the primary producers to the consumers, and the recycling of detritus and waste materials. These fundamental features will then be affected by human interference, for example, the habitats will be dominated by pollution tolerant organisms under human-mediated organic enrichment and also a change in the sizes of organisms present in stressed systems. Introduced, invasive and alien species are known to affect all the environments and human changes will result in the removal of prey populations, such as the prey of birds and fishes, and the consequent reduction in the carrying capacity of the system.

#### (i) Estuary

Table 8a indicates that estuaries are dominated by the physical processes relating to the maintenance of their saline-freshwater balance, for example the effects of freshwater flow into the estuary when balanced against the tidal inflow. This is overlaid with an essentially sediment-dominated system and as such, the maintenance of mudflats, and intertidal and subtidal sandbanks is critical for the maintenance of the sediment-dwelling infaunal populations. The natural physico-chemical stresses produce a community of reduced species complement, compared to the marine area, but with high and variable population size. In turn, the sediment infauna then modifies the substratum and influences the erosion and deposition processes by disturbance or the creation of biological films. Those sediment dwellers then support the higher predators, especially the overwintering bird populations and nursery fish communities which are often of conservation importance.

Estuaries tend to be turbid and so the primary producers are adapted to a reduced light regime. As such, although most estuaries world-wide are organic-rich systems, the internal production of organic matter (autochthonous production) may be lower than on the open coast, with a larger proportion of organic matter found in the estuary coming from external sources (allochthonous inputs) such as the riverine input and open coast. The water column phytoplankton primary producers are often relatively low in abundance such that up to 40% of the carbon supply in estuarine systems may be contributed by sediment-inhabiting micro-algae which grow on intertidal sediments (Prof. D. Paterson, University of St Andrews, Scotland, pers. comm.). A poorer intertidal productivity will then be supplemented by large standing stocks of mid-estuarine saltmarsh and upper estuarine reedbeds (McLusky & Elliott, 2004). However, it is of note that nutrient-poor estuaries also occur, particularly in the North Wales context (CCW, pers. comm.). The anthropogenic increase of nutrients in these oligotrophic estuaries to make them more similar to ‘clean’ organic rich estuaries elsewhere should therefore be regarded as serious a change as the more usual concerns over naturally organically-rich estuaries becoming hypernutrified or even eutrophic.

**(ii) Intertidal (open coast)**

The classical separation of the shore into soft and/or mobile sediment (sand, gravel or cobble beaches) or hard substratum (rock platforms, large boulder systems) provides the greatest contrast between the different coastal intertidal areas. These dominant features are the result of the dominant coastal processes. The prevailing hydrographical conditions, in addition to the result of past geological events (e.g. glaciations and transgressions), create the underlying structure including the presence, delivery and movement of sediment on particulate shores and the prevention of sediment building up on rocky shores. These physical characteristics then determine the biological communities found at different sites. Similarly, the beach community will be highly influenced by the exposure regime, i.e. the wave and swell climate which will be influenced by the position of the coastline, the direction (thus giving the fetch) and the speed of the wind. In turn, the intertidal organisms will be affected by the exposure regime combined with their ability to withstand desiccation. The hydrographic processes will also influence and determine the biota dispersal mechanisms (see Raffaelli & Hawkins, 1996; Little & Kitching, 1996; Little, 2000 for further information).

**(iii) Subtidal (open coast)**

As with the intertidal areas, the subtidal areas include both hard and soft substrata and mixtures thereof as well as continua showing transitions between these types. It is arguable that the soft sedimentary seabed is of greater importance in area whereas hard substratum has a smaller area but these may be of high profile in terms of biodiversity, for example around the islands of Skomer and Lundy. The dispersion and degradation of organic matter, except in very sheltered areas, will prevent its build up and thus the creation of stressed communities. Some areas of the seabed, such as off much of the Welsh coast (E.I.S. Rees, University of Wales, Bangor, pers. comm.) have sediment storage areas as lag coarse deposits which are derived from the re-working of glacial till and deposits of outwash gravel. The cyclic deposition and re-suspension can result in progressive advection and more concentrated deposition with significant consequences for benthic communities and production.

#### (iv) Pelagic

The maintenance of the pelagic ecosystem requires the successful maintenance of water column processes such as hydrographic patterns, salinity and temperature profiles, oxygen balance and nutrient fluxes. The biota are susceptible to the presence of poor water quality such as low oxygen or high ammonia areas which increases the ability of the water column to act as a barrier by migrating species. The underlying (residual) hydrographic patterns, such as the role of stratification driven circulation in the Celtic Sea and the flow up through St George's channel on the Welsh side, are important for the dispersion of marine organisms and thus the maintenance of populations.

## 2.4 Human-Induced Changes in Marine Ecosystems

As introduced in Section 1, the DPSIR framework gives a philosophy for describing and determining the causes of ecosystem state change and the resultant impacts on the human uses of the system. Human-induced change in marine ecosystems derives ultimately from a set of main Drivers, such as the need for navigation, land for infrastructure or agriculture or for food from fisheries and shellfisheries. Each of these Drivers then leads to a set of Pressures such as, respectively from the above examples, dredging and dredged material disposal, land-claim and the loss of wetlands, and beam-trawl effects and organic enrichment from fish farms. At its most basic, the causes of human-induced change can be reduced to two categories:

- biological or non-biological substances/materials/objects *placed in* the environment as the result of human activities, such as hazardous chemicals, organic matter /sewage, diffuse pollution, infrastructure (e.g. bridges, barriers), and non-indigenous species;
- biological or non-biological substances/materials/objects *removed by* Man from the system such as aggregates, oil and gas, habitat (as loss and land claim), renewable energy, fisheries.

These inputs and extracts from the system may be small or large entities and can be categorised as biological, physical and chemical materials (examples in Table 9). Hence the nature of human impacts in the marine environment will be related to the fate and effects of these inputs and the effects of removing components from the system. Furthermore it is necessary to make a distinction between materials which may be introduced without causing a deterioration to the ecosystem health and those which cause a deterioration. For example, a material introduced without harm is termed a contaminant whereas that which causes biological damage is termed a pollutant (McLusky & Elliott, 2004). Similarly, a species moved by human activities but which does not displace others or cause a harmful response, at any level of biological organisation is termed an alien or introduced species whereas one causing actual or potential damage is termed an invasive species.

**Table 9: Examples of small and large materials placed in and extracted from marine waters and habitats**

| | Inputs | | Extracts | |
|---|---|---|---|---|
| | **Small** | **Large** | **Small** | **Large** |
| ***Biological*** | Pathogenic micro-organisms from sewage | Introduced and invasive species from aquaculture and transport | Shellfish | Finfish |
| ***Physical*** | Silt particles from human mediated erosion | Infrastructure such as barrages, bridges, rigs | Water for cooling, substratum for aggregates, energy | Area of wetland by land-claim |
| ***Chemical*** | Nutrients from diffuse pollution from agriculture and riverine inputs | Oil spillages from marine accidents | Salt | |

The causes and consequences of human activities can be summarised as a set of conceptual models that aim to show the pathways of cause and effect and therefore are valuable for informing policy makers and managers. Those for fisheries, trawl fishing, dredging, dredged material disposal, offshore wind power, oil spills and estuarine barrages are given in McLusky and Elliott (2004). In essence, biological change and especially a reduction in health and well-being can then be measured at various levels of biological organisation – the cell, individual, population, community, and ecosystem (see McLusky & Elliott, 2004 for further details of approaches and methods).

The overall adverse influence of any particular activity on the natural system can be termed its ***ecological footprint***, a term first used by Wackernagel and Rees (1996) and developed by Palmer (1999). In general terms, this relates to the area per capita required to produce food, to be occupied by infrastructure and to provide energy or at least to absorb the results of providing energy (e.g. carbon dioxide sequestration). It is also the area defined during the Environmental Impact Assessment for any single activity such as trawling or building a marina. While the ecological footprints of some activities may be relatively small, again building localised infrastructure, others may e large, e.g. the global production and transport of food. As shown by Palmer (1999), the quantification of the ecological footprint is most widely developed for terrestrial systems, the land required for food production, the energy requirements by Man and the area required to sequester $CO_2$. The concept, however, is poorly developed for marine systems and especially dynamic systems whereby an impact may be at a distance from the site of the stressor. For example, shrimp trawling has an ecological footprint away from its area because of the bycatch of juvenile fishes ultimately affecting the adult stocks (Blaber *et al.*, 2000).

# 3. THE RECOVERY OF MARINE ECOSYSTEMS

## 3.1 Legislation and Policy Drivers for Ecosystem Recovery and Restoration

Many legislative and policy drivers with respect to ecological restoration originate from international agreements (such as the Earth Summits, the Ramsar Convention and the Convention on Biological Diversity), together with European legislation and the accompanying national enabling legislation (see below). As a result, each country in Europe has developed its own standards and approaches to nature conservation, which also includes ecological restoration activities (Madgwick & Jones, 2002). Legislative drivers at the international, European and national levels are indicated in Table 10 and are discussed below.

**Table 10: Legislation and policy drivers which explicitly or implicitly include habitat restoration**

| International | European | UK National | UK Regional |
|---|---|---|---|
| ***Ramsar Convention*** - Provides for compensation measures which may include elements of restoration to be taken if any designated Ramsar site is adversely affected | ***Habitats Directive*** - Aims to maintain or restore at favourable conservation status those habitats and species of wild fauna and flora of Community Interest | ***Habitats Regulations*** - The Conservation (Natural Habitats &c.) Regulations, 1994 were introduced to transpose the Habitats Directive into UK national legislation and thus ensure both habitats and species of Community Importance are protected | ***Shoreline Management Plans*** (SMPs) provide a large-scale assessment of the risks associated with coastal processes and present a long term policy framework which may include elements of habitat restoration and habitat creation |
| ***Biodiversity Convention*** - States that each member state shall 'rehabilitate and restore degraded ecosystems…' and 'adopt measures for the recovery and rehabilitation of threatened species…' | ***Wild Birds Directive*** - States that each member state shall 'conserve, maintain or restore the biotopes and habitats' of birds protected within sites designated as SPAs | ***UK Biodiversity Action Plan*** (BAP) - Places duty on UK government Ministers to have regard to the purpose of biodiversity conservation in accordance with the Convention on Biological Diversity; aim to create and restore coastal habitats to offset predicted losses due to sea-level rise | ***CHaMP*** - In the UK, Coastal Habitat Management Plans (CHaMPs) are non statutory plans which identify potential future changes to coastal habitats and potential compensation measures for any losses |
| | ***Natura 2000*** - Both the Habitats and Wild Birds Directives require that 'compensatory measures' are taken in the case that a *Natura 2000* site is damaged, which may include economic, resource or ecological compensation | ***Wildlife and Countryside Act***; and the ***Countryside and Rights of Way Act*** – under both of these Acts UK courts can require a landowner who has damaged a SSSI to restore the land to its former condition | |

### 3.1.1 INTERNATIONAL AGREEMENTS

*1971 Convention on Wetlands of International Importance (Ramsar Convention)*

- The Ramsar convention is an intergovernmental treaty which provides the framework for national action and international co-operation for the conservation and wise use of wetlands and their resources.
- It establishes specific guidelines on wetland restoration which were approved by all member governments in 1999.
- It also provides for 'compensation' measures, which may include elements of restoration, to be taken if any designated Ramsar site is adversely affected by activities considered to be in the 'urgent national interest'.

*1992 Convention on Biological Diversity (Biodiversity Convention)*

- Requires contracting parties to develop National Biodiversity Strategies and Action Plans, including restoration targets for habitats and species.
- The Convention establishes three main goals: the conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of the benefits from the use of genetic resources.
- Article 8(f) states that each member state shall 'rehabilitate and restore degraded ecosystems and promote the recovery of threatened species, *inter alia*, through the development and implementation of plans or other management strategies'.
- Article 9(c) states that each member state shall 'adopt measures for the recovery and rehabilitation of threatened species and for their reintroduction into their natural habitats under appropriate conditions'.

### 3.1.2 EUROPEAN DIRECTIVES

The development of the European Union (EU) has provided the possibility for coherent standards, practices and procedures with respect to nature conservation and environmental management, and specifically with respect to ecological restoration carried out across the EU. Two key European Directives in this respect, the Wild Birds Directive and the Habitats Directive, are discussed below.

*1979 EU Conservation of Wild Birds Directive (79/409/EEC)*

- The Directive requires member states to classify Special Protected Areas (SPAs) to protect, manage and regulate all bird species naturally living in the wild within the European territory of the member states, including the eggs of these birds, their nests and their habitats.
- Under Article 3(2), member states must also conserve, maintain or restore the biotopes and habitats of these birds by: creating protection zones; maintaining the habitats; restoring destroyed biotopes; and creating biotopes.

*1992 EU Habitats and Species Directive (92/43/EEC)*

- The overall aim of the Directive is to ‘contribute towards ensuring bio-diversity through the conservation of natural habitats and of wild fauna and flora in the European territory of the member states to which the Treaty applies’.
- Article 2 requires member states to implement the measures necessary for maintaining or restoring at ‘favourable conservation status’ those habitats and species of wild fauna and flora of Community Interest, listed as priority in Annex I and II of the Directive respectively.
- The Directive, under Article 3, provides for a European-wide ecological network of Special Areas of Conservation (SACs) under the title of Natura 2000.

*Natura 2000*

- The measures for managing Natura 2000 sites are given in Article 6 of the Habitats Directive.
- Both the EU Habitats and Birds Directives require that ‘compensatory measures’ are taken when and if a Natura 2000 site is damaged for reasons of overriding public interest.
- For example, following the construction of the Cardiff Bay tidal barrage in south Wales, part of the Severn Estuary Natura 2000 site was destroyed and thus a major freshwater wetland area was rehabilitated to provide compensation for the damage (Madgwick & Jones, 2002).

### 3.1.3 NATIONAL LEGISLATION

In order to achieve the targets set within European legislation, it is the responsibility of the member state to establish relevant national enabling legislation to implement the Directives. An example of this for the UK to meet the requirements of the EU Habitats Directive is described below.

#### 3.1.3.1 United Kingdom

*Conservation (Natural Habitats, &c.) Regulations, 1994*

- Within the United Kingdom (UK), the EU Habitats Directive is transposed into national legislation by the Conservation (Natural Habitats, &c.) Regulations which came into force on 30 October 1994 and have subsequently been amended in 1995 (Northern Ireland), 1997, 2000 (England) and 2004 (Scotland).
- The Habitat Regulations extend out to the limit of UK territorial waters (i.e. 12 nautical miles from the baseline).
- Under the Habitats regulations, competent authorities (such as Ministers, government departments, public bodies, or people holding public office) are responsible for ensuring that the all regulations with respect to the Habitats Directive are adhered to.

- The Regulations require the Secretary of State to propose a list of potential sites which are important with respect to habitats and/or species, as listed in Annex I and II respectively of the EU Habitats Directive. If the importance of the proposed sites is agreed by the European Commission and other member states then the proposed sites will be designated as Sites of Community Importance (SCIs).
- Member states have a six year period following the designation of SCIs to designate the sites as a Special Areas of Conservation (SAC) under the EU Habitats Directive.
- The Regulations also require the compilation and maintenance of a register of European sites and form a network under the title Natura 2000, which includes both SACs and SPAs.
- The country conservation agencies within the UK (English Nature, Scottish Natural Heritage, Countryside Council for Wales, and Environment and Heritage Service (Northern Ireland)) are given the authority to enter into management agreements with landowners surrounding European Sites in order to secure its conservation.

## 3.2 The Current Understanding and Concepts of Recovery

The term recovery is initially used here to collectively describe all cases where the ecosystem has been improved with regard to the ecosystem goods and services that it supports, thus it initially includes restoration, adaptation, re-creation, remediation, enhancement etc. The semantics of ecosystem recovery includes a plethora of terms and have led to confusion in the use of the terms (cf. Hawkins *et al.*, 1999; Bradshaw, 2002). The present section aims to harmonise the use of those terms and to define and clarify where possible. Table 11 illustrates the plethora, linking and use of the terms used in restoration science and management and thus the potential for confusion. Because of this, Bradshaw (2002) makes a plea 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*. While this is an admirable desire, Bradshaw's (loc. cit) use of the term restoration does not cover all management actions such as habitat creation, mitigation and compensation which are increasingly being tested legally (see also Perrow & Davy, 2002a, b).

After considering both recent and classical literature, it is suggested here that the natural and human-mediated recovery/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 both a passive approach and an ongoing process which depends on a habitat's potential for recovery (this is synonymous with the terms non-intervention/natural recolonisation used by Emu (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 11, which also groups the terms under the four types of process/action listed above). The second class also includes the term given by Emu (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 considered not to be helpful in the present discussion and so is not used further. 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 term includes both an improvement of a habitat and the creation of a habitat (e.g. artificial reefs) in areas not previously having that type of habitat. However, this implies a quality judgement that the science and engineering is 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.

**Table 11: Natural and Anthropogenic Recovery of Ecosystems and Habitats**

| **(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) | minimise effects |
| Adapting | what is occurring in the system | Remediation (*1) | Compensation (*2) | replace a loss of ecosystem goods and services |
| Adaptability | inherent property of the system | Rehabilitation (*1) | Creation (*3) | replace lost ecosystem goods or services or produce new ecosystem goods and services |
| Resilience | inherent property of the system | Re-establishment (*1) | | |
| Carrying capacity | inherent property of the system (desired state) | Re-introduction (*1) | | |
| | | Reclamation (*1) | | |
| | | Replacement (*1) | | |

The terms in Table 11 and their definitions (presented below in Section 3.3.) have 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 (Figure 4). Degradation is accepted to imply 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 in many environments, especially the marine environment, to quantify simultaneous changes structure and functioning as co-ordinates in a bivariate model (as used in Bradshaw, 2002), the conceptual model here merely has a single axis for increasing ecosystem quality which encompasses both attributes. Several authors suggest that ***restoration*** implies a return of the ecosystem to its original or previous state in terms of both structure and function and Bradshaw (2002) also considers the terms ***rehabilitation***, in which a return to the original state is not totally achieved, and ***replacement*** of the original by something different. In terrestrial cases, these terms are encompassed by the general term ***reclamation*** although this term has not been used with this meaning in the marine environment (historically it has been used as synonymous with and the forerunner of the more accurate term 'land-claim'). Furthermore, Bradshaw (1987, 2002) suggests that mitigation implies the rehabilitation of another system - this is more correctly now termed compensation (i.e. *ex situ* creation of habitats) as opposed merely to mitigation as the lessening of an effect *in situ*.

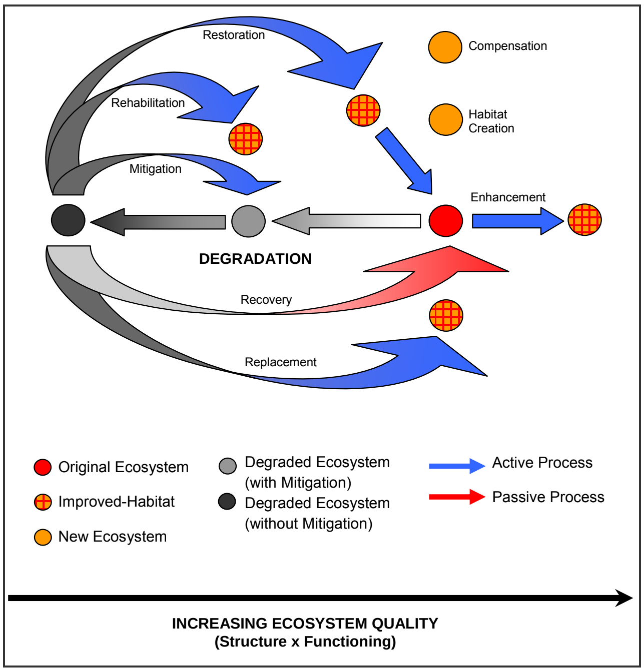


**Figure 4 A conceptual model illustrating the nature of natural recovery of a degraded ecosystem and the terms used in human-mediated (active) restoration. The model indicates that habitats can be produced ( ) which are an improvement on the degraded state but not necessarily to the original state ( ), whereas other ecosystems ( ) are newly created systems. The recovery (red 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.**

Perrow and Davy (2002a) emphasise that ecological and habitat restoration science and management is essentially the manipulation of the physical and chemical environment, the manipulation of the biota and the monitoring and appraisal of restored systems, and the restoration process. Manipulation and monitoring are anthropogenic responses to environmental stressors. 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 climate change (termed 'exogenic unmanaged pressures'). In the latter case, which implies global change, the management actions within an area cannot address the causes of the change and so can only use adaptational strategies to address the consequences.

As indicated in the previous section, the degradation of the marine and estuarine system can be attributed to the introduction or removal from the area of physical and chemical materials, physical structures and organisms. Restoration/recovery should therefore be aimed at reversing such adverse effects and as such, De Jonge and de Jong (2002) indicate 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;
- Providing compensation for events outside the system, for example the responses such as managed realignment required to counter sea level rise or isostatic rebound.

## 3.3 Recovery Terminology and Concepts

The science and terminology of habitat recovery and restoration has long been associated with terrestrial and freshwater areas and has only recently been considered for estuarine and coastal environments; as such the marine environment has been given very little attention (see Perrow & Davy, 2002a, Livingston, 2006). From a terrestrial viewpoint, Bradshaw (2002) emphasises the terms restoration, rehabilitation, remediation, and reclamation and so the discussion here aims to translate these and other associated terms to the estuarine, coastal and marine environments. It is emphasised that this field includes the recovery, by natural active or passive means, of the physical, chemical and biological environment. However, although some aspects are well understood for the marine environment, such as sediment-hydrography relationships and 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).

Recovery implies that the system will regain some previous state after being in a degraded or disrupted state which can be interpreted as being in poor ecological health. The return to the original state will be with (active recovery) or without (passive recovery) human intervention; in the case of the former it may have a medical analogy whereby treatment is administered (Hawkins *et al.*, 1999). The recovery may occur naturally but of course may be speeded-up with intervention. This implies that recovery is a process occurring in the system once the stressor causing the adverse change 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, 2004). The ecosystem goods and services provided and its carrying capacity will have recovered or been regained to the pre-impact state.

Ecological recovery of a disturbed habitat, including newly created and restored sites, depends upon a number of biological factors, such as the sources and transport of propagules which in certain cases may require management to facilitate/enhance the natural process (Pratt, 1994). Similarly, target species with long life spans and poor dispersal techniques may need particular management through introduction (ABP Research, 1998). As such, newly restored wetlands may have to be inoculated with material from similar aquatic ecosystems to ensure effective colonisation by microbes, plants and invertebrates (Pratt, 1994), unless the created site is adjacent to established sites and where opportunity exists for exchange and transport of natural propagules (I. Black, pers. comm., 1996 *in* ABP Research, 1998).

Recovery can be accelerated through management actions, for example the appropriate use of oil-spill clean-up techniques but, similarly, it can be hindered by inappropriate action such as the wrong type of clean up following an oil spill (Hawkins *et al.*, 1999).

### 3.3.1 PASSIVE RECOVERY

**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). This is regarded as an inherent property of the ecosystem in that certain ecosystems may have a greater potential for recovering from stress than others, for example a subtidal sandbank whose physical and biological structure is created by a high energy regime will be more resilient 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, i.e. recoverability depends on the stressor, the impacted species/community and the temporal and spatial intensity of the stressor.

**Ecosystem or Ecological Resilience/Robustness**

Ecosystem resilience can be defined most simply as *'the ability of an ecosystem to return to its original state after being disturbed'* (*MarLIN* Glossary, 2005), it may also be termed 'robustness' (Loreau *et al.,* 2002). Ecosystems may be regarded as being in stability domains, i.e. being in one particular state (Bengtsson *et al.,* 2002) such that ecological resilience is the amount of disturbance that an ecosystem in one stability domain can absorb before they are caused to change to another domain. 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*'.

Resilience is therefore regarded here as an inherent property of the ecosystem which indicates its ability to absorb change; it may be related to 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, often related to its feeding (trophic) structure, to another. The latter, regarded as 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 foodwebs centre around connectance (the number of links between species) and the length of food chains, amongst others (Dunne *et al.,* 2004). These properties of food webs are scale dependent, i.e. they change with diversity and complexity, and this is particularly the case with estuarine, coastal and marine foodwebs which have large numbers of opportunist and generalist feeders. In particular, high connectance communities tend to be more robust (resilient) to species loss than low connectance communities such that marine communities have a greater structural robustness than other ecosystems (Dunne *et al.,* 2004).

Ecosystem resilience can thus be reduced when environmental and/or human-mediated stressors act together and lead to such a shift in state (Dunne *et al.,* 2004). When resilience is lost or significantly decreased, a system is likely to change to a qualitatively different state. Gunderson (2000) discusses 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, there is the need to incorporate the magnitude of inherent complexity/variability of an ecosystem into the determination of resilience.

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 resilient ecosystem such as an estuary has the capability to withstand and/or absorb anthropogenic stress. It is suggested here that resilience and recoverability are synonymous. Similarly, the amount of resilience a system possesses relates to the degree of disturbance required to fundamentally disrupt the system causing a dramatic shift to another state of the system, 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, habitat fragmentation) may exceed threshold levels, resulting in an abrupt system response (e.g. Kaiser *et al.,* 2005; The Resilience Alliance, 2002).

The conceptual model of an anthropogenic pressure (a stressor) acting on the ecological state hypothesises that the recovery process may be different from the impact process and that this hysteresis will differ with type of system and with type of stressor (Figure 5). However, empirical evidence for this model is still required for the marine environment in order to determine the magnitude and repercussions of these changes.

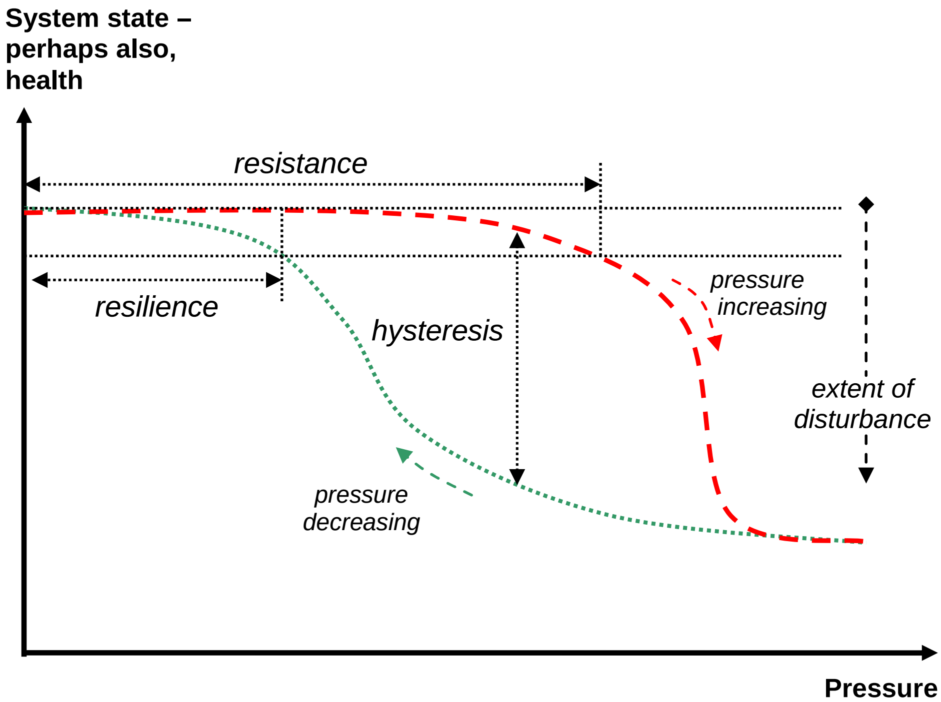


**Figure 5: A conceptual model of changes to state of a system with increasing pressure (from Defra, 2004b)**

## Adaptation

In general terms, adaptation can be defined as the ability to alter for new use. In an ecological context, adaptation refers to the processes or coping strategies to be used by communities to increase their resilience (decrease their vulnerability) to ecosystem changes. For example, the reduction of freshwater flow into an estuary will lead to a reduction in the brackish (euryhaline) component of the fauna and an increase in the marine (stenohaline) component. While individual species may not adapt to the changed salinities, the new community will be adapted to the new situation which may function in the same way as the original one. For example, an increased estuarine salinity will change a community from being dominated by the ragworm *Hediste diversicolor* to one dominated by the more marine catworm *Nephtys hombergi* (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 as the result of climate change, in the Northern Hemisphere southern species migrate into an area and northern species migrate out of it (see Laffoley *et al.*, 2005 for related publications/presentations).

**Carrying/Assimilative Capacity**

Carrying capacity can be defined in terms of both environmental and societal demands i.e. what the natural system wants and can accommodate in the system and what are society's aspirations (Cohen, 1996; Elliott & Cutts, 2004; MacLeod & Cooper, 2005). Baretta-Bekker *et al.,* (1998) defines it as '*the maximum population size (density of an organism (*sic*)) 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 (i) 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, (ii) 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 in various ways by Cohen (1996) and termed K, based on a logistical curve 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 in terms of Liebig's law of the minimum 'under steady state conditions, the population size of a species is constrained by whatever resource is in the shortest supply'. In relation to commercial stocks, Cohen (1996) gives 5 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 is 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) become more precise in defining it as the point at which the mortality rate of a population exceeds the birth rate 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 (see below regarding comments about the detection of change against a reference condition).

Given that these definitions tend to be based around commercial populations, in the case of natural systems the term will be taken here to mean simply *'the maximal population (and/or community) that can be supported by the area's resources, principally space, food, and reproductive partners'*. For example, in temperate estuarine intertidal areas, a high carrying capacity may be defined as the ability of the area to support high numbers of over-wintering wading birds and/or juvenile fish. Until recently, ecological carrying capacity has been defined in terms of the food and space available for use by organisms and this concept has been used more for wading birds than other organisms (see for example Stillman *et al.*, 2005). Measures of both habitat quality and resource quantity are therefore required in order to determine the population supported by an area although, in the particular case of overwintering bird populations, factors at their breeding sites away from the British 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 John Goss-Custard, CEH, 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 John Goss-Custard, CEH, pers comm.).

While the above text indicates the ecological nature of the term, it can also be used to indicate 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. As such, the latter can also be described as the system's ***assimilative capacity***, a term often used to indicate the ability of an area to receive (as in disperse, degrade and assimilate) polluting discharges (McLusky & Elliott, 2004). MacLeod and Cooper (2005) take these concepts further and consider the term carrying capacity to have a range of definitions in addition to ecological: *physical, social and economic carrying capacity*. ***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, a feature related to tourism on the coast. ***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 coastal development for tourism becoming so intensive that the desirability of the area declines.

### 3.3.2 ACTIVE RECOVERY

(a) the human-mediated response to a degraded environment:

**Rehabilitation**

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). This implies that 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 process will be brought about by management actions but requires a decision regarding the preferred final state. For example, a low organic state of an intertidal area from which a sewage discharge has been removed will be preferable even though it supports fewer wading birds.

**Restoration**

Restoration implies, in an ecological context, *'the return of a [coastal] habitat from a disturbed or totally altered condition to a previously existing natural condition ……. by man'* (ABP Research, 1998). Bradshaw (2002) suggests that the non-ecological uses of the term imply a return to an original state which is perfect and healthy but argues that an ecologically-preferable definition is '*ecological restoration 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 is taken to imply 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 (here this is termed recovery). Restoration can accelerate recovery although this could lead to an alternative state. Similarly, the original state may not be known.

Fonseca *et al.* (2002), in discussing seagrass areas, 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.' At present, it is difficult to quantify these different aspects and to interpret them for the wider marine environment.

Habitat restoration (re-creation) can be seen simply as a means of compensating for losses caused by the effects of development and other forms of damaging human activity on the environment (Doody, 2003). Lewis (1990) 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 habitat type. However, Zedler (1984) considers that restoration does require a return to the exact pre-existing condition although it is suggested here that this is rarely achieved, especially if the original state is unknown. The latter will depend on the time-scale involved as the time-scale against which a habitat is restored may be 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 a former state supporting saltmarsh) (Elliott & Cutts, 2004).

Once areas of conservation value have been identified and statutory provisions implemented, the subsequent management of sites and habitats may include: allowing nature to take its course, or intervening to maintain the '*status quo*' which includes preventing change thought to be detrimental to the designated interest (Doody, 2003). As such, coastal habitat restoration may simply involve the reversal of trends, including those due to human factors such as agricultural intensification, or abandoning a cultivated area. However, degraded or damaged habitats may require further intervention in order to change the site or habitat, i.e. flooding of former agricultural land to restore mudflats and/or saltmarsh, or replacement of lost or diminished sediment supply (Doody, 2003).

In the coastal, estuarine and marine environments, most restoration, as an active, human-mediated process, has been small-scale although studies do show the potential for larger scales (e.g. Perrow & Davy 2002a, b). On a small scale, several studies have emphasised the central role of keystone species and ecological engineers (structural species) in aiding or effecting restoration (Fonseca *et al.*, 2002; Hawkins, 2004). For example, seaweed restoration has been achieved by active means but this has usually been as the result of commercial concerns, e.g. to increase seaweed for harvesting or to allow recovery in areas where seaweed and faunal collection has ceased. Similarly, seagrass beds can be restored in cases where there has been only a partial removal or effect of disease. Seeding and planting has had a limited success with human-mediated losses outweighing the gains after restoration. Despite this, Fonseca *et al.* (2002) conclude that as long as the water column and sediment conditions are suitable then recovery will follow; thus in the case of seagrasses, a suitable nutrient regime, water transparency, inundation period and substratum type for attachment will allow recolonisation as long as the seagrass propagules are available. 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).

**Remediation**

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, 2004). Hence the emphasis is on 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, however, it is recognised that complete restoration of a habitat is rarely achieved.

**Re-creation**

This term 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 seawall has been removed and a saline intrusion regained.

As indicated on several occasions above, the terms restoration, rehabilitation, re-creation and remediation are used interchangeably in the literature and in discussions. To all intents and purposes they may be synonymous but there is the need for refining or standardising their definitions.

**Re-establishment**

This term indicates the replacement of a structural component of the ecosystem in sufficient quantities to allow it to regain its overall nature and thus restore the ecological functioning. For example, the transplanting of seagrass stands, reedbeds, 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 (Hawkins *et al.*, 1999). Similarly, ***re-introduction*** will also be contemplated to redress the loss of a species and the desire for a population to be re-established.

**Reclamation**

This term 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 or a required use. Similarly, *replacement* may be implied if the new area has a use different from that originally or when being degraded (Bradshaw, 2002). To replace could also be used for the substitution of a habitat, for example the introduction of artificial reefs on seabed previously subtidal sediment; however, this has also been termed habitat enhancement and so is discussed below with that term. Both of these terms are unlikely to be required 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.

(b) the response to a single stressor:

**Mitigation**

Mitigation can be defined as *'the act of making any impact less severe'* (Elliott & Cutts, 2004). This is likely to be a condition of any licence, authorisation, permit, or consent for any activity to occur based upon the findings of an environmental impact assessment (Glasson *et al.*, 1994; Wood, 2003; Morris & Therivel, 2001). It is likely to be 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, the disposal of dredged material will be licensed and thus managed in order to minimise any negative impact on the receiving ecosystem possibly through the choice of the receiving area (e.g. disposing of dredged fine sediment resulting from harbour clearance into a fine sedimentary area).

It is questionable whether changes due to events outside a system, such as climate change leading to sea-level rise, can be mitigated or whether this is regarded as compensation. 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. In addition, Bradshaw (2002) correctly takes the view that mitigation is not directly connected to restoration but he suggests that it can be an outcome of restoration (or rehabilitation or reclamation), and may involve the improvement of another ecosystem. However, as indicated below, such a conclusion is better termed compensation rather than mitigation.

**Compensation**

On land, in freshwaters, and in estuaries, an increasing number of land use planning decisions require compensatory, mitigation or restoration measures to minimise the effects of developments. The open marine environment will follow this trend and so there will be an increasing number of compensatory 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 & Jones, 2002).

If it is not possible to make an impact less severe (i.e. to mitigate) then compensation would be required. For example, the loss of a habitat through port expansion cannot be mitigated but the natural asset can be compensated by creating a habitat elsewhere (Elliott & Cutts, 2004) as compensation is generally defined as *'to make up or make amends for damage'*. In an ecological context, Elliott and Cutts (2004) suggest that there are three types of compensation available: (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).

Where habitat loss is unavoidable, compensation for this has become an accepted requirement within EIA. In the context of existing legislation, this is combined with attempting to ensure the continued survival of the range and variation of habitats and distribution of species in the face of increasing stressors and as such, re-creation or creation of habitat would be carried out together with site protection measures (Doody, 2003). Where feasible, the new habitat will be located as close as possible to the area it replaces, although compensating habitat loss is rarely successful in replacing habitats with similar ones (Doody, 2003). Habitat creation often then involves an unavoidable trade-off between new and existing habitats (ABP Research, 1998). With particular reference to site usage by waders, whilst the development of a compensatory site may ensure the maintenance of the overall population, it cannot be assumed that this aids the survival of those individuals which formerly fed on the destroyed area (ABP Research, 1998). For example, on the Humber Estuary, an outer estuary saltmarsh site will be 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 ecological goods and services of the estuary than would have been the case without compensation (English Nature, pers. comm.).

**Habitat Enhancement**

In general terms, enhancement has been used to imply the establishment of an alternative ecosystem although the preferable use of the term is to raise in degree, heighten, intensify, or to increase the value, importance or attractiveness (Bradshaw, 2002). In an ecological context, habitat enhancement can simply be defined as a management approach which directly or indirectly results in an increase in ecological value of the habitat, for example increased numbers of over-wintering wading birds on an estuary. One such Welsh example would be the increased carrying capacity of the Menai Strait to support wading birds (oystercatcher) associated with mussel fisheries (Caldow *et al.*, 2004). Bradshaw (2002) suggests that this is the action of improving a habitat which already has a good ecological functioning. However, Emu (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.

**Habitat Creation**

In the context of marine habitats, creation can be defined as an anthropogenic intervention which produces a habitat not previously there (*cf.* habitat re-creation), for example where Man converts a non-wetland habitat into a wetland habitat where there has not been one within recent history, a century for example (Lewis, 1990; ABP Research, 1998). This action presupposes that, given the historical loss of coastal and estuarine habitats, then any new habitats are regarded as environmentally beneficial (Livingston, 2006). However, because the gain of one habitat implies the loss of another, whether this is enhancement of the overall system remains questionable. Similarly, the placement of a new habitat within an area should be regarded as creation rather than re-creation. For example, the use of artificial reefs on an otherwise sandy seabed can be regarded as increasing the biodiversity of an area but it is not replacing lost habitat.

Habitat creation will be difficult in many coastal and estuarine sites which have static 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, seawalls or other infrastructure. Without intervention, such as realignment of the boundaries, then an overall loss of intertidal habitat and thus conservation interest will occur in areas due to relative sea-level rise (through global change and isostatic rebound and termed coastal-squeeze), or where storm frequency and intensity is increased (McLusky & 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. However, in all cases, consideration should be given to the creation of new replacement habitats outside existing site boundaries (Doody, 2003).

## 3.4 Frameworks for Management Action to Achieve Restoration

Semi-enclosed, coastal and fringing systems and estuaries have an increasing case-history of restoration, partly because these are also the areas with severe impacts. Enclosed waters such as estuaries, bays, and lagoons are amenable to restoration through water quality improvement and so their physical environment can also be manipulated such as by increasing flushing (Hawkins *et al.*, 1999, 2002). In contrast, in an open marine system, there is a limited opportunity for rehabilitation/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) - but also it may not be possible in a large unbounded system to do anything. 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). For example, Clark (2002) shows that 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 onto which biota can colonise.

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

In offshore areas, there is a limited ability for restorative action other than to stop the activity, for example, the restoration of adverse impacts of overfishing by the prevention of the activity such as the introduction of no-take zones (e.g. scallop dredging off Isle of Man). It is of note that recent considerations of the Dutch RIKZ (National Institute of Coastal and Marine Management, Ministry of Public Works) emphasise that a wind farm off their coast would have the beneficial effect of preventing beam trawling, considered to be a more damaging activity. It is likely that with the operation of Round 1 windfarms and the creation of Round 2 windfarms in the UK waters, these considerations will also be regarded as a former of enhancing recovery and restoration of the seabed as the creation of *de facto* Marine Protected Areas and No-Take Zones.

The interconnected nature of open marine systems allows rapid recolonisation once amelioration of water quality and reversal of the deterioration of physical structure has been put in place. Hence the philosophy of focussing on the physico-chemical environment and prevention of the over-exploitation of the biota and allow natural recovery to occur (Hawkins *et al.*, 2002; Edwards & Winn, 2006). Thus restoration procedures 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 takes 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.

Given the above features, a suitable decision-making framework for marine, coastal and estuarine restoration can be produced (Table 12). There is the ability in some cases to speed up succession and use the organisms' natural ability to disperse and settle providing that the physico-chemical conditions are appropriate. The case-studies show that here possible natural recovery is seen as most appropriate mechanism for restoration and most likely to restore the ecosystem goods and services. Rehabilitation, as in the case of dock restoration, is considered as a pragmatic option to enable potential return to a specific state than complete return to a pre-impact natural condition. This approach is useful 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, then kelps can be restored by a combination of allowing natural recovery after reducing/suspending the extraction, increasing or restoring the hard substrata, or removing the sea urchin grazers. This shows that successful restoration requires good science and hypothesis testing, and is a mixture of science and engineering; there are good cases of pilot projects but there is the need for a larger scale projects.

**Table 12: Summary of decision-making for marine, coastal and estuarine restoration (modified and expanded from Hawkins *et al.*, 1999)**

| **Action Level 1** | **1. Stop chronic stressors from acting or remove stressors (e.g. discharges, overfishing)** | |
|---|---|---|
| | **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 | Restore physical and chemical environment |
| | Stop unnecessary interventions and cumulative impacts | Restore biological and physical structural integrity |
| | Assess time-scale of recovery | 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'; 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; possibly costly |

This scheme of management will require to be accompanied by a no-net loss policy and achieving the recovery of an interim ecological resource and ecological goods and services requires full rehabilitation of a site (*in situ* restoration), alternative compensatory sites to be used, or combination of both. However, the creation of compensatory sites is relatively recent in the estuarine and coastal field and non-existent in the open marine area and hence poor case-history; accordingly there may a problem of creating a habitat in a compensation area where it did not occur before, in that conditions inherently were not suitable.

Fonseca *et al.* (2002) in discussing seagrass restoration, suggests 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 to be determined. The underlying knowledge for seagrasses, saltmarshes, and corals appears suitable for providing this information (Livingston, 2006; Perrow & Davy, 2002a, b) but especially lacking for other marine habitats and ecosystems.

### 3.4.1 Examples of Management Action

The above features can be illustrated using examples of management action to restore or recreate particular habitats.

#### (1) Managed Realignment

Managed realignment (previously known as setback or managed retreat and also known as de-polderisation in Belgium and the Netherlands) is a modern and increasingly important management option where wetlands are created either as water storage areas to combat flooding, or at flood defence areas to combat sea-level rise, erosion and/or isostatic rebound (land sinking) and the resultant habitat-loss (Edwards & Winn, 2006). These schemes are created by moving sea walls back and allowing the area between the new and old sea walls to flood. The primary reason for these schemes is linked to human safety, then economic benefits and lastly environmental gains and is thus considered a 'win-win-win' situation (Elliott & Cutts, 2004). They are also used as compensation schemes to offset the loss of habitat from port developments, e.g. Welwick on the Humber estuary (Edwards & Winn, 2006; ABP, 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 compensation scheme.

#### (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 actions on dis-used 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. In essence however, it is improving an artificial structure in order to make it an artificial lagoon ('lagoonoid'?) after the recovery of water quality and the mixing regime. This leads to a new colonisation by a hard substratum fauna and flora which is likely to be totally different from that soft-substratum biota originally in the area prior to the dock being created (hence the debate that the new system is an improvement on the degraded dock but is not a natural system).

Despite this, the case-study does indicate the role of structuring species such as suspension feeding mussels. A management strategy, faced with eutrophic conditions, was 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. The action was carried out together with a control on the causes of the high nutrients, i.e. the diffuse and point source inputs. The 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 clear, oligotrophic waters to the turbid, eutrophic state, and the role of bioengineers in that process. In this case, the movement from the latter to the former by introducing filter feeders or reducing nutrient inputs showed the feedback mechanism to aid movement from one state to another.

### (3) Saltmarsh Restoration in the Wadden Sea

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 & Jones, 2002). The lost saltmarshes will be restored through a programme of opening summer dykes to increase natural morphology, drainage patterns, and 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 in that the restoration of a corridor through a saltmarsh disturbed by pipe laying is of a different order to restoring saltmarsh after coastal re-alignment (Hawkins, 2004). While the former will involve 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. 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. Perhaps more than other examples, saltmarsh restoration emphasises the linking of the engineering and ecological aspects and that engineering solutions are required to overcome land claim, impounding, subsidence, draining, erosion, etc.

Saltmarsh restoration also has the advantage of a large case-history which has been used to produce a pragmatic approach to increasing the area and quality of saltmarshes:

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

### (4) Seagrass Restoration

Seagrass restoration shows the importance of 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. These measures are metrics of what is required to regain the appropriate ecological goods and services, for example, seagrass shoot density. This then gives an indication of the sites which can be chosen as compensation, i.e. the criteria for selection of a restoration 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 subject 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;
- the restored and lost area are similar quality habitat (Fonseca *et al.*, 2002).

**(5) Beach Restoration**

Within North West Europe, coastal beaches provide an example 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). However, in other areas worldwide, beach restoration may include the provision of nesting areas for turtles and birds. Beach nourishment or recharge is widely used in the UK and the Low Countries on soft coasts and in estuaries to counter erosion and movement of sediment, and to compensate for changes due to sea level rise. Similarly, the beneficial use of dredged material is being used to re-create or extend mudflats in estuaries along the east coast of England. 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. pers. comm. DECODE project - Dr S. Bolan (Cefas) and E. Mitchell (IECS)). 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 recruiting juvenile stages at settlement. As yet, however, there are no indications 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.

As a further illustration, the beaches of North-east England were severely degraded by the dumping of colliery waste for many decades and, in tandem, the beaches were subsiding due to the extraction of the sub-surface coal (Humphries, 2004). While their topography and tidal profile was 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. While this has produced a natural infill by sand to approximate the state prior to degradation, the non-intervention has prevented a more natural beach profile and hence a recovery of their fauna (Humphries, 2004).

**(6) Upper Estuarine Water Quality**

While many of the examples discussed here relate to the permanent loss of habitats, such as through land claim of previous salt marsh areas, in many industrialised area the temporary loss of habitat is of greater relevance and has important ecological consequences. Many estuaries are naturally hypernutrified and organically enriched such that with additional organic matter inputs (i.e. those from sewage discharges), the upper estuarine turbidity maximum area develops a water quality barrier (McLusky & Elliott, 2004). The low dissolved oxygen levels in these regions prevent, on some seasonal and tidal conditions, the migration by diadromous fishes and the occupation by estuarine resident fishes (Elliott & Hemingway, 2002). For example, the Forth, Clyde, Mersey, Scheldt, Delaware, and Thames estuaries have all experienced these water quality problems and the resultant effects on their fish communities. Remedial measures involving the reduction in sewage discharges and, in the case of the Thames estuary, oxygen introduction during certain conditions, have led to the recovery of the fish communities. These actions have also been accompanied by re-stocking with salmonids to increase the population viability.

### 3.4.2 RECOVERY OPTIONS FOR TARGETED ECOSYSTEMS

The features of a selection of habitats/ecosystems - estuary, intertidal, subtidal, and pelagic - were indicated above in relation to the dominant and fundamental processes which occur there and the way in which these were impacted by human activities. Table 13 indicates the recovery options suitable for each of those habitats/ecosystems and reinforces comments made earlier that the nature of restoration possible differs with type of stressor causing change, nature of the habitat, other uses of the area, and available funds and technologies.

**Table 13: Level 4 processes (responses to change) within the chosen ecosystems**

| 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:<br>(i) users<br>(ii) resource<br>(iii) habitats | ✓ | ✓ | ✓ | ✓ |
| Barrier removal:<br>(i) water quality<br>(ii) physical structures | ✓ | ✓ | - | - |

✓ applicable and valuable

- applicable but not valuable

0 not applicable

# 4. MARINE MANAGEMENT APPROACHES

## 4.1 Philosophies and Tools for Management

### 4.1.1 DATA AND INFORMATION REQUIREMENTS FOR MANAGEMENT

As indicated in the Introduction, the Ecosystem Approach is essentially a management philosophy which sets out high level principles that should be applied to management to ensure sustainable development. Similarly, the DPSIR approach also summarises the causes and consequences of human-induced change and thus the human-mediated responses to that change. The management of an ecosystem and an understanding of the way in which it changes under human influences requires a large amount of data, information, and knowledge about the structure and functioning of the system; this then allows management decisions to be made (Table 14; McLusky & Elliott, 2004). The aim of such a framework, which is sufficiently generic to cover all human activities, is to encourage managers to obtain the appropriate information for management. By accumulating information in progressing from Stage 1 to Stage 9, environmental managers such as conservation and environmental protection bodies will be in a better position to determine the effects of human activities on the marine system.

Each of the ‘decisions’ in Table 14 relates to the way in which the ecosystem functions and the behaviour of materials or activities placed in the environment. For example, the placing of dredged material into the sea after dredging will have an effect which depends on the nature of the receiving environment (i.e. whether it has water current above a threshold speed), and on the nature of the material being dumped (e.g. whether it is sand or mud). However, the Ecosystem Approach is necessary to ensure that all aspects are taken into account and thus that the overall health of systems and the services that they deliver are recognised and protected. The most important components of the ecosystem and the functional services that they provide are outlined below.

**Table 14: The provision of data, information and knowledge for management (modified from McLusky & Elliott 2004)**

| Stage | Topic | Information produced |
|---|---|---|
| 1 | Behaviour/characteristics of the system | of the intertidal, subtidal, lagoonal, estuarine, open coastal areas. |
| 2 | Physical/chemical nature of system | its hydrography, topography, bathymetry, salinity regime, nutrient status, etc. |
| 3 | Physical and chemical behaviour of additives to system | their dispersion in a solid or liquid phase, solubility, transport, sequestration. |
| 4 | Behaviour/characteristics of an activity in the environment | whether there is a barrier to the flow of materials and biota, or the disruption of processes. |
| 5 | Habitat at risk from modification or materials addition | whether there is a surface feature (monolayer), or effects in the water column, water-substratum interface, sediment, supralittoral, intertidal, circalittoral, infralittoral, shelf. |
| 6 | Inert or biologically effective action | whether there is a direct toxic nature, secondary toxic nature (after modification in or of habitat). |
| 7 | Biotic and non-biotic component(s) at risk | the phytoplankton, zooplankton, pelagic nekton, demersal nekton, hyperbenthos, epifauna, infauna, microphytobenthos, macroalgae, saltmarsh, reedbeds, wading birds, wildfowl. |
| 8 | Behaviour of contaminants within organisms | their uptake, sequestration, storage, excretion, passage to progeny, passage to prey. |
| 9 | Structure & functioning of biological system | the response at the individual, population, community and ecosystem levels of biological organisation. |

### 4.1.2 OBJECTIVES AND INDICATORS FOR MANAGEMENT

Objectives for environmental management of an area, species, habitat, etc. have been developed since the 1970's as statements (e.g. the EQO/EQS approach, Elliott, 1996; McLusky & Elliott, 2004), for example, statements such as the desire for the health of the seabed to be sufficient to sustain sea fisheries. Objectives for pollution control were first suggested in Royal Commission documents relating to sewage control at the beginning of the 20$^{th}$ Century and reinforced by the Royal Commission on Environmental Pollution in the 1970's. More recently, there are developments to define objectives for the holistic management of the estuarine, coastal and marine areas (Apitz *et al.,* 2006) and to identify environmental objectives necessary to support the UK Vision and Strategic Goals in the marine environment (Rogers & Tasker, 2005). These initiatives take the principles and practices used for the terrestrial and freshwater systems out through estuaries and coastal areas to the open sea.

With the extensive implementation of the EC Water Framework Directive (WFD), the measures needed to reach the over-arching objectives of Good Ecological Status and Good Chemical Status by 2015 are being determined (Apitz *et al.*, 2006; http://www.wfduk.org).

Similarly the over-riding objective of reaching Favourable Conservation Status for Natura 2000 sites (derived from the implementation of the Habitats and Wild Birds Directives, HSD/WBD; Halahan & May, 2003) also requires monitoring and management to be enacted. However, to date both the WFD and HSD/WBD relates by statute and practice to the nearshore coastal and estuarine areas and so the EU Marine Strategy and the proposed Marine Framework Directive will be needed to manage the marine environment throughout the UK seas beyond the current Water Framework Directive (WFD) boundary (Borja, 2006).

The tools and practices for the management of the estuarine, coastal, and marine areas follow the recent Review of Marine Nature Conservation (Boyes *et al.*, 2003a) and the experience of the Irish Sea Pilot Project (Vincent *et al.*, 2004). As yet, the proposals for the management of the marine environment to be included in the proposed UK Marine Bill are unknown but it is expected that they will build on recent projects relating to marine spatial planning and zonation schemes (Boyes *et al.*, 2005).

In common with inshore and estuarine practices, there is the need for the well-accepted sequence from objectives, to indicators, to monitoring, to management (Elliott, 1996; McLusky & Elliott, 2004). Rogers & Tasker (2005) emphasise the need for a hierarchical structure giving a logical framework leading from the UK's guiding principles for sustainable development and its Vision for the Marine Environment, to quantitative indicators and their limit/target reference points. They emphasise that the '*existing UK Strategic Goals, which underpin the Vision, should be supported by high level statements (Ecological Objectives) of what is to be attained for each ecological component. In turn, these should be made operational by further objectives that have a direct and practical interpretation and that are specific to regions, uses and/or sectors (Operational Objectives). Indicators, with appropriate target and/or limit reference points, will be required to track the progress of these Operational Objectives. While Ecological Objectives should only be set for measures of state of the ecosystem, Operational Objectives should relate to the pressure generated by human activities as well as the state of ecosystem components*'. Following this, Rogers and Tasker (2005) proposed a set of high level environmental objectives and they also noted the need for the development of social and economic objectives for the open sea areas.

The development of high level objectives, as proposed in Rogers and Tasker (2005), in turn reflects developments within the regional seas convention OSPAR. This convention, in common with HELCOM, its corresponding organisation for the Baltic, have derived Ecological Quality Objectives (EcoQO) as an indication of the high level demands for the marine system (Painting *et al.,* 2005). These EcoQO should be sufficiently quantitative to allow for monitoring and to determine when Ecological Quality (EcoQ) has been achieved. EcoQ is thus regarded as an overall expression of the structure and functioning of marine ecosystems and the numeric EcoQO are then referred to as the desired level of the EcoQ relative to a reference condition (Skjoldal *et al.,* 1999). As an illustration of the overall direction for marine management, Painting *et al.* (2005) indicates the linkages between these OSPAR initiatives and ICES criteria for ecosystem health. It is emphasised here that this direction is further reinforced by the EU Marine Strategy (Borja, 2006), the implementation of the EU Water Framework Directive and the proposed Marine Framework Directive.

As is demonstrated above however, such high level objectives need to be more quantitative before they can be used in an operation manner, i.e. unless they are quantitative and fully defined then it is not possible to determine whether they have been met, nor what monitoring is required prior to management if they are not met. Business management takes the view that in order to manage the system then its features have to be measured hence the need for monitoring, under both spatial and temporal scales thus respectively giving the extent and duration of the perceived change. Using this analogy for the marine environment, objectives set against which monitoring is carried out should be ***SMART*** (Table 15). (While the acronym SMART has been used widely, as indicated in the Table 15, there are some differences in the meaning of the acronym, hence the alternatives given in the Table). Such quantitative objectives can therefore be regarded as indicators of change and due to their fundamental use in determining and managing change there has recently been a large amount of effort on the development of marine indicators (e.g. Rogers & Greenaway, 2005; Aubry & Elliott, 2006; Bortone, 2005).

Indicators have variously been termed action levels, triggers for action, thresholds and reference levels but the important point is that monitoring is subsequently required to determine if and when the indicators of change have been exceeded and thus when management measures will be required. As such, this philosophy and approach is similar to the adoption by environmental protection bodies, such as the Environment Agency in England and Wales, of Environmental Quality Objectives (EQO) and Environmental Quality Standards (EQS). EQO are statements which describe the demands of an area, for example the ability for fish to migrate at all states of the tide, whereas the accompanying EQS are numerical thresholds which should be achieved to ensure that the EQO is met, e.g. that the water column dissolved oxygen should not fall below 5 mg $l^{-1}$ otherwise a water quality barrier is created). This approach relies on a good scientific underpinning of the links between the EQO and EQS, i.e. fish will not migrate under sufficiently low oxygen levels.

**Table 15: Examples of SMART Objectives for a seagrass bed**

| Attribute | Example for the health of a seagrass bed |
|---|---|
| **S**pecific | Relate to a particular species, e.g. *Zostera*, particular features of the bed, health of the plants, area of the resource |
| **M**easurable | Quantify the change – e.g. area of bed, number of shoots per $m^2$, percentage of shoots with black necrosis, change in these with time |
| **A**chievable / **A**ppropriate / **A**ttainable | Measurements can be made, proven relative to seagrass health |
| **R**ealistic / **R**esults focussed / **R**elevant | Assessment relates to the aim for the bed, i.e. what deterioration in quality of the seagrass has occurred |
| **T**ime-bounded / **T**imely | The seagrass bed should not deteriorate by more than a given amount over a given time; by date [year] a certain amount of seagrass will be recovering |

Increasingly, within the Ecosystem Approach, in order to determine whether an objective is met, indicators are being developed and used as management tools to address environmental issues (e.g. see OECD, 1994; EEA, 1999; Belfiore, 2003; Bortone, 2005). In many cases, indicators are derived for a particular stressor or type of activity, for example Grieve *et al.* (2003) present available indicators for fisheries and aquaculture. An environmental indicator is a qualitative or quantitative parameter characterising the current condition of an element of the environment (e.g. tonnage of material dredged), or its change over time (e.g. loss of saltmarshes). Such environmental indicators have 3 basic functions (Aubry & Elliott, 2006):

> *To simplify:* Amongst the diverse components of an ecosystem, a few indicators are selected according to their perceived relevance for characterising the overall state of the ecosystem.
>
> *To quantify:* The value of the indicator is compared with reference values considered to be characteristic of either 'pristine' or heavily impacted ecosystems. For example, the ecological status of water bodies assigned under the European Union Water Framework Directive (Elliott *et al.,* 1999) relates to the determination of changes from reference or expected conditions.
>
> *To communicate:* The use of indicators facilitates communication on environmental issues with stakeholders and policy makers, by promoting information exchange and comparison of spatial and temporal patterns.

Environmental indicators are measures of the state of, and pressures on, the environment (Environment Agency, 2005a), and have been used for a number of years to describe a particular aspect of the environment in order to guide policy and management decisions (Gubbay, 2004; Aubry & Elliott, 2006). Such indicators should ideally meet the criteria indicated in Table 16 (modified and expanded from Environment Agency, 2005a; Gubbay, 2004; Rogers & Greenaway, 2005; Aubry & Elliott, 2006). In building on the SMART concept described in Table 15, in order to be effective and used for successful management, indicators should have all or almost all of a set of properties in Table 16.

**Table 16: The required properties of indicators for successful marine management**

| Property | Explanation |
|---|---|
| Measurable | Indicators should be easily measurable in practice using existing instruments, monitoring programmes, and analytical tools available in the relevant areas, to the required accuracy and precision, and on the time-scales needed to support management. They should have minimum or known bias (error), and the desired signal should be distinguishable from noise or at least the noise (inherent variability in the data) should be quantified and explained. Measurable over the area where they may be used and capable of being updated regularly. |
| Cost-effective | Indicators should be cost-effective because monitoring resources are limited. Monitoring should be allocated in ways that provide the greatest benefits to the scientific understanding and interpretation, society and the fastest progress towards sustainable development. |
| Realistic / Attainable (achievable) | Indicators should be realistic in their structure and measurement and should provide information on a 'need-to-know' basis rather than a 'nice-to-know' basis. They should be attainable (achievable) within the management framework. |
| Concrete / Results focussed | Indicators are desirable which are directly observable and measurable rather than reflecting abstract properties which can only be estimated indirectly. Concrete indicators are more readily interpretable by the diverse stakeholder groups that contribute to management decision-making. |
| Time bounded | The date at which the indicator level should be attained should be indicated in advance. They are likely to be based on existing time-series data to help set objectives, and also based on data that are readily available and also show trends over time. |
| Timely | The indicators should be appropriate to management decisions relating to human activities and therefore they should be relatively tightly linked in space and time to that activity. |
| Interpretable | Indicators should reflect properties of concern to stakeholders, and their meaning should be understood by as wide a range of stakeholders as possible. The public understanding of the indicator should be consistent with its technical meaning. In particular, they should be relatively easy to understand by non-scientists and other users. |
| Grounded in theory / Relevant and Appropriate | Indicators should reflect features of ecosystems and human impacts that (according to well-accepted peer-reviewed scientific theory) are relevant to the achievement of operational objectives. They should be scientifically sound and defensible and not based on theoretical links which are poorly defined or validated. They should be relevant and appropriate to management initiatives and understood by managers. |
| Sensitive | The trends in the indicator should be sensitive to changes in the ecosystem properties or impacts, which the indicator is intended to measure. As `indicated above, they should be sensitive to a manageable human activity and to the change that they are being used to measure. |
| Responsive | Indicators should be responsive to effective management action and provide rapid and reliable feedback on the consequences of management actions. Such feedback loops should be determined and defined in advance of using the indicator. |
| Specific | Indicators should respond to the properties they are intended to measure rather than to other factors, and/or it should be possible to disentangle the effects of other factors from the observed response. |

Many indicators describe the quality of a particular aspect of the environment, such as the level of nitrate and phosphate pollution in a watercourse, and PCBs in sediment. However, in recent years, the emphasis has moved from concentrating on one aspect of the ecosystem, to seeking indicators that reveal how ecosystems as a whole are functioning. Indicators have to be simple, measurable, and responsive and ultimately the criteria for identifying suitable indicators must relate to the reasons for using them (Gubbay, 2004). Similarly, environmental indicators should ideally support the ecosystem-based approach to management, e.g. by providing a meaningful assessment of the 'health' of marine ecosystems, which is cited throughout definitions of the ecosystem based approach (Gubbay, 2004).

A number of different approaches to selecting environmental indicators with reference to the ecosystem based approach have been discussed (e.g. Grieve *et al.*, 2003). However, the general consensus appears to be that a suite of indicators rather than a single one is required to adequately report on ecosystem health, structure, and function (Rogers & Greenaway, 2005; Bortone, 2005; Aubry & Elliott, 2006). As noted by Gubbay (2004), the recurring themes in these different approaches include 'vigour', 'structure', and 'resilience'. Table 17, modified from Gubbay (2004), defines these terms and provides examples of potential elements linked to biodiversity which could help to describe them.

A further and recent approach to assessing, classifying and managing ecosystem health is the V-O-R Approach which is summarised below:

- **V**igour – turnover, throughput, or productivity of the system, i.e. the amount of material which will be transferred between herbivores and plants, or carnivores and their prey;
- **O**rganisation – species diversity, degree of connectiveness (food webs, trophic interactions, predator-prey relationships), i.e. the structure of the ecosystem and the links between the various components;
- **R**esilience – ability to maintain structure and function despite stress; ability to withstand sustained or repeated stress, e.g. the means by which an estuarine community can absorb anthropogenic changes.

This approach was suggested by Costanza and Mageau, (1999) and has been modified from Boesch and Paul (2001). Each of these features includes the ecosystem structure and functioning, the nature of biotic and environmental processes, and the ability of an ecosystem to recover from external stressors. A conceptual diagram of ecosystem ecosystem health (using these terms) is presented in Figure 6. A healthy ecosystem is one which has the appropriate communities and habitats, each of which produces sufficient organic material to support the consumers in the system and has an inbuilt ability to withstand change. Such healthy ecosystems lie within the ellipse of the conceptual model (A, B, C, D) although any anthropogenic and adverse change will reduce the components, increase of decrease the production of organic matter, and/or reduce its abilities to accommodate change (E, F). The successive degradation of an area will cause it to change in these properties (from time $t_1$ to $t_5$). Hence, the properties of ecosystems combine to create a healthy system whereby any adverse change will reduce its fitness for survival in its undisturbed state.

It is emphasised that the model reproduced in Figure 6 is a conceptual framework and as such has not yet been applied to individual marine areas, including estuaries and coasts. Indeed, until further studies can quantify the attributes on the axes, this will be difficult.

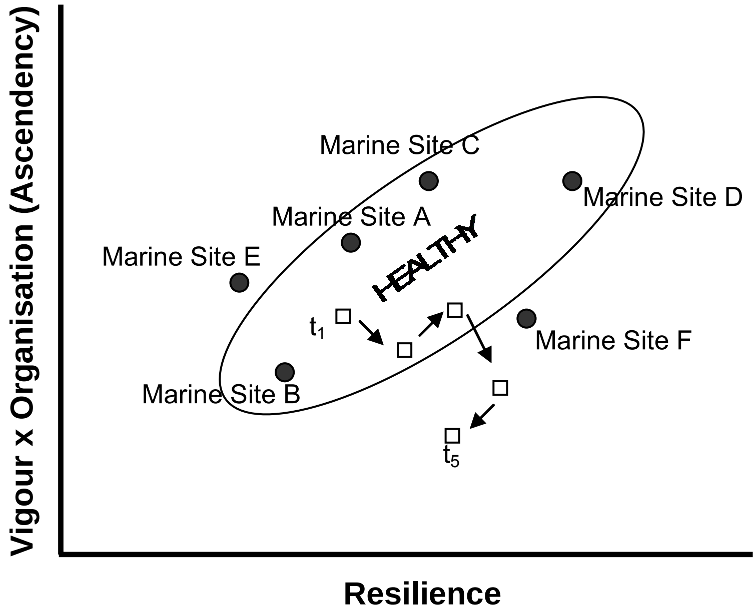


**Figure 6: Conceptual diagram - ecosystem health (i.e. vigour x organisation (= ascendancy) *vs.* resilience). V-O-R properties of different areas with temporal change (t1 to t5) (modified from Costanza & Mageau, 1999)**

**Table 17: Examples of possible indicators of ecosystem resilience, structure, and vigour (modified from Gubbay, 2004)**

| Theme | Definition | Potentially Useful Elements of Relevant Indicator |
|---|---|---|
| Ecosystem resilience | The ability of an ecosystem to resist change and recover after disturbance. | Keystone species<br>Habitat complexity<br>Body-size structure/size spectra |
| Ecosystem structure | The components of the ecosystem. | Species/habitat diversity<br>Species assemblages<br>Trophic structure |
| Ecosystem vigour | A measure of the activity, metabolism and productivity of an ecosystem. | Productivity |

Reviews of marine environmental indicators and relevant developments within this field are provided by Gubbay (2004), Rogers and Greenaway (2005), Bortone (2005), and Aubry and Elliott (2006). As an example, ten ecosystem indicators have been proposed within the OSPAR EcoQO, the EU Headline biodiversity indicators and within the England Biodiversity Strategy. These indicators can be mapped onto the DPSIR framework as shown in Figure 7 (after Rogers & Greenaway, 2005).

| | D | P | S | I | R |
|---|---|---|---|---|---|
| Physical / Chemical Habitat | | Hazardous substance input<br>River inputs | Oxygen<br>Habitat Quality<br>SSSI Condition | | |
| Nutrients | | and discharges | Winter nutrients<br>Nutrients<br>Chlorophyll | | |
| Phyto / Zoo Plankton | | | Phy. indicators<br>Chlorophyll a<br>WFD | | |
| Benthos | | | Sensitive opportunistic dog whelk | Zoobenthos kills | |
| Fish | | Fish stock status | Fish<br>Fish community<br>Sand-eel / birds<br>Stock status | SSB | Fleet Capacity |
| Seabirds | | Sand-eel / birds<br>Oiled Guillemots | Seabird pops.<br>Seabird pops. | Mercury / organochl. | |
| Marine Mammals | | Cetacean by-catch | Seal pops.<br>Seal breeding site | Porpoise by-catch | |
| | | | Habitats, Birds Directive, SSSI | | |
| Most Or All Ecosystem Components | | | T & D species<br>BAP species & habitats<br>Diversity trends<br>Threatened sp. | | Public & Biodiversity<br>Protected areas |

OSPAR EcoQO
EU Headline
EBS
EA
OSPAR RID & CEMP

**Figure 7: Mapping a selection of proposed and operational marine ecosystem indicators onto the DPSIR framework (after Rogers & Greenaway, 2005)**

The further development of marine environmental management will require that in order to determine if the ecological functioning of coasts and marine areas is as expected/required, then a full suite of objectives and indicators will need to be developed. These will then require implementation for the Welsh coast and seas, perhaps, for example, in conjunction with Quality Status Report of State of the Seas report. This follows the lead taken by bodies such as UNEP in proposing objectives and quantitative indicators for a fisheries-based ecosystem approach (Table 18). The holistic approach to management, as required by the Ecosystem Approach, will also require development of economic and social objectives for the maritime environment.

**Table 18: Examples of Ecosystem Objectives, Indicators and Reference Points for Ocean Management Areas (OMAs) (UNEP, 2001)**

| Objectives | Indicator | Reference Points |
|---|---|---|
| Maintenance of ecosystem diversity | Areas of the continental shelf disturbed by fishing activities | Percentage of each habitat type that is undisturbed |
| Maintenance of species diversity | Number of individuals of the species at risk<br>Geographic area of distribution | Maximum by-catch annually<br>Percentage of distributional area relative to period of moderate abundance |
| Maintenance of genetic variability within species | Number of spawning populations of targeted species<br>Selection differentials | Percentage reduction in spawning areas<br>Minimum selection differential |
| Maintenance of directly impacted species | Fishing mortality<br>Spawning stock biomass<br>Area of distribution | F0.1<br>Minimum stock biomass necessary for recruitment and forage<br>Percentage of distribution relative to period of moderate abundance |
| Maintenance of ecologically dependent species | Abundance of key predator<br>Condition of key predator<br>Percentage of prey species in diet of predator | Minimum abundance level of predator<br>Minimum condition level of predator<br>Minimum percentage in diet of predator |
| Maintenance of ecosystem structure and function | Slope of size spectrum<br>k-dominance curves<br>Pauly's FIB index<br>Aggregate annual removals by fishing for each trophic level | Percent change in slope of size spectrum<br>Maximum elevation change in k-dominance curve<br>Minimum level for index<br>Maximum percentage removal from a trophic level |

### 4.1.3 MONITORING RESPONSES TO HUMAN-INDUCED CHANGES

As indicated earlier, human activities in the marine and estuarine environment can be regarded as a set of Drivers and Pressures, for example the main Driver of wanting food from the sea which then creates a set of Pressures on the seabed through trawling or through harbour construction, etc. These subsequently lead to State Changes, for example to the health of the seabed or the fish populations, and then to Impacts on the human system such as changes in the amount of food or contamination of food through pollution.

Society then requires responses to these problems in order to allow for, and achieve sustainable management of the marine and estuarine environment.

The management of any area should be centred on the objectives set for the area, whether the production of food from fisheries, sustainable energy, recreation, or a high conservation value. If these objectives are well-defined then the management actions can be directed towards achieving them. For example, an SAC will have its management objectives defined as conservation objectives to protect the features and species for which the area was designated. The water quality in an estuary may be managed to allow the passage of migratory salmonids at all stages of the tide.

It is axiomatic that the management of any system is more likely to be successful if the objectives are well-defined. Similarly, if the objectives are quantitative then this can support true monitoring and thus the detection of change from a natural (non-impacted) situation. For example, in order to allow the successful passage of migrating salmon through an estuary, a water column oxygen level of greater than 5 mg $l^{-1}$ will be required. The discharge of sewage into the estuary can be managed to prevent the reduction in oxygen and thus the creation of a barrier in water quality. Monitoring can subsequently be carried out to determine whether fish are migrating through the area and whether the oxygen levels in the water remain above the 5 mg $l^{-1}$ threshold. If the latter level is breached then management actions are required such as the better treatment of sewage being discharged into the estuary. This is regarded as true monitoring or ***compliance or operational monitoring*** – against a predefined standard and whereby action is pre-defined if the standard is breached. It is therefore emphasised that management and monitoring requires the creation and adoption of quantitative indicators of change. Hence, monitoring is required to:

- assess the state of an area;
- inform decisions with regard to measures for the protection of areas;
- provide an evaluation of measures already taken (Annex 15 of the 2003 Bremen Declaration of OSPAR).

These concepts have recently been extended in marine management to encompass several types of monitoring – compliance or operational monitoring as described above, surveillance monitoring, and investigative or diagnostic monitoring. These aspects are now defined in the EU Water Framework Directive whereby ***surveillance or condition monitoring*** (previously called surveillance) is merely the act of sampling, possibly on a repeated basis and with good spatial coverage, a feature or features. These may include the health of the population or the size of a habitat such as a seagrass bed. Following the surveillance monitoring, the spatial and temporal patterns are interrogated to indicate whether the area seems to be improving or deteriorating; if the latter, management actions would then be put in place. This is regarded as an *a posteriori* approach and therefore does not rely on a pre-defined indication of what change is acceptable. Surveillance monitoring may also be synonymous with condition monitoring as specified by the EU Habitats Directive whereby the condition of an SAC is monitored and ***Favourable Conservation Status*** is attained (Halahan & May, 2003). In contrast, as indicated above, true monitoring (compliance or operational monitoring) implies a predefined idea of what is required or accepted as the unimpacted state. Under the EU WFD, and the recently proposed (October 2005) EU Marine Framework Directive, this will be the achievement of ***Good Ecological Status*** (GEcS, for the WFD), or ***Good Environmental Status*** (GEcS, for the MFD) based on deviation from a reference condition. (It is of note that the definition and separation or otherwise of Good Ecological Status, Good Environmental Status and Favourable Conservation Status is currently under discussion (February 2006) although there is the presumption that these could be taken as synonymous (Defra, pers. comm.).

If an area does not meet one of these quality designations (Good Ecological Status, Good Environmental Status, or Favourable Conservation Status), i.e. it has deviated from that which is desired, for example fish do not migrate through an area or the amount of seagrass bed has been reduced, then ***diagnostic or investigative monitoring*** (also called applied research) is required to determine the cause of that change. This may require further field studies, field experiments or, in the case of pollution from an industrial discharge, laboratory experiments and toxicity testing (see McLusky & Elliott, 2004, and Hardman-Mountford *et al.*, 2005, for further discussion of these topics).

There has long been confusion in monitoring terminology which has variously been used to describe three different activities: to sample and survey an area, to undertake surveillance (with a spatial extent or temporal duration), or for monitoring to ensure that a predetermined or pre-required status has been met (Holl & Cairns, 2002; Hardman-Mountford *et al.*, 2005). These require fundamental decisions regarding sampling design and the location of control areas and should incorporate many features in order to provide the information necessary for management although many of the features many be site or stressor specific (Table 19). Perhaps the greatest challenge however, is the concept of moving baselines in that within dynamic systems, and especially open marine systems, there is unlikely to be a well-defined baseline against which to measure change. This temporal variability, together with the large-scale inherent spatial variability in marine systems, make the detection of a change (the signal-noise ratio) particularly difficult.

**Table 19: Desirable characteristics for monitoring parameters (modified from Holl & Cairns 2002, Cairns *et al.*, 1993, McLusky & Elliott, 2004)**

| Characteristic | Description |
|---|---|
| Biologically important | Focuses on species, biotopes, communities, etc. important in maintaining a functioning ecological community |
| Socially relevant | Understandable to stakeholders and the wider society or at least predictive of or a surrogate for a change of importance to society |
| Sensitive and relevant to a known stressor or stressors | Sensitive to stressors, based on an underlying conceptual model, without an all-or-none response to extreme or natural variability |
| Broadly applicable | Usable at many sites and over different time periods |
| Diagnostic | Relevant to a particular stressor and again based on an underlying conceptual basis |
| Measurable | Capable of being operationally defined and measured, with accepted methods and Analytical/Quality Control/Quality Assurance and with defined detection limits |
| Interpretable | Capable of distinguishing acceptable from unacceptable conditions in a scientifically and legally defensive way; capable of maximising the signal:noise ratio by minimising or quantifying inherent and natural variability |
| Cost-effective | Measurements financially non-prohibitive, allowing for an optimum and defensible sampling strategy, providing the maximum amount of information possible |
| Integrative | Presents an holistic assessment, providing and summarises information from many measured indicators across environmental and biotic aspects |
| Historical or reference data available | Allows comparisons with previous data available to estimate variability and to define trends and possibly acceptable and unacceptable conditions |
| Anticipatory | Sufficient to allow the defence of the precautionary principle, as an early warning of change, capable of indicating deviation from that expected before irreversible damage occurs |
| Non-destructive | Methods used cause minimal and acceptable damage to the ecosystem and are legally permissible |
| Continuity | Capable of being measured over time as the area recovers and is restored, on ecological and human timescales |
| Appropriate scale | Relevant for the spatial scale of the restoration, providing both near field and far field assessments |
| Low redundancy | Provides unique information compared to other measures |
| Feedback to management | Provides information within real time to allow feedback into management to allow remedial action to prevent further deterioration and to indicate any change in strategy |

## 4.2 MANAGEMENT FRAMEWORKS LINKING ENVIRONMENTAL, POLICY AND SOCIO-ECONOMIC ASPECTS

The successful management of marine ecosystems requires an holistic approach which has to take account of all aspects covering the natural environmental and human cultural aspects - the environmental, socio-economic, administrative and legal as well as having the techniques and technologies to effect that management. These features can be regarded as a set of ***seven tenets***, each of which requires to be fulfilled by the sum of management actions for sustainable management to be achieved (Table 20). The actions to ensure the protection of all levels of biological organisation (from the cell to the ecosystem) are embedded in the first tenet, environmentally sustainable but management of the environment cannot operate away from the human cultural aspects. Again using commercial applications, the use of the 7-tenet approach has features of the ***PEST*** analysis in which the organisation of an environment can be analysed against a background of its ***P****olitical,* ***E****conomical,* ***S****ocial and* ***T****echnological* constraints (Palmer & Hartley, 2005). These features are importance in not only preventing the deterioration in ecosystem health described above, but also in restoring and allowing a degraded ecosystem to recover.

**Table 20: The seven tenets of environmental management (after Elliott & Cutts, 2004)**

| Tenet | Explanation |
|---|---|
| Environmentally sustainable | That the measures will ensure that the ecosystem features are safeguarded |
| Technologically feasible | That the methods and equipment for ecosystem protection are available |
| Economically viable | That a cost-benefit assessment of the environmental management indicates sustainability |
| Socially desirable/tolerable | That the environmental management measures are as required or at least are understood by society as being required |
| Legally permissible | That there are regional, national, European or international agreements and/or statutes which will enable the management measures to be performed |
| Administratively achievable | That the statutory bodies such as governmental departments, environmental protection and conservation bodies are in place and functional to enable the successful and sustainable management |
| Politically expedient | That the management approaches and philosophies are consistent with the prevailing political climate |

The ecological and societal links listed above have to be embedded within the prevailing governance which operates at regional, national, European and international scales. The UK Government has developed a range of policies and non-statutory measures in recent decades (e.g. the establishment of nature reserves through land purchase and/or management agreements) for the conservation of marine biodiversity (Gubbay, 2004). Some of these are a response to global and European obligations, such as the Convention on Biological Diversity (CBD) and the EC Habitats and Birds Directives, and others are part of national agendas, such as the legal framework to establish Marine Nature Reserves, which was set out in the 1981 Wildlife & Countryside Act (Gubbay, 2004). Statutory designations to protect some or all of the identified features may require specific actions to be taken ranging from restrictions on damaging activities, control through the planning system, and active conservation management (Doody, 2003). In addition, there will be over-riding economic repercussions to the use of the marine environment.

As indicated earlier in this report, the Ecosystem Approach to the sustainable use of the marine environment is based on the adoption of the 12 principles laid down by the Convention of Biological Diversity. These principles also cover the environmental and human cultural aspects and as such, the concepts presented throughout this report can be summarised and then combined under the unifying framework of the Ecosystem Approach and its guiding principles to ensure sustainable ecological management (Figure 8, Table 21). Firstly, the causes and consequences of change due to human activities in the marine environment can be summarised as the DPSIR approach, with an understanding of the fate and cause and effect relationships of human impacts. Secondly, the study and quantification of the causes and impacts of change require a robust scientific method in order for their assessment to be defendable. Hence, there is the need to derive the aims and objectives for the differing habitats and then set the hypotheses of change which can be tested using field survey and field experimentation if suitable. Thirdly, management requires the measurement of causes and consequences of change and an indication of when change is so large that action has to be taken. This quantification requires the development of quantitative, numerical indicators and those indicators require to be SMART in order to know if and when they have been met. Finally, for sustainable responses and sustainable, successful, and defendable environmental management to occur, the 12 principles of the CBD Ecosystem Approach have to be integrated with the 7 tenets (described above) and a PEST analysis.

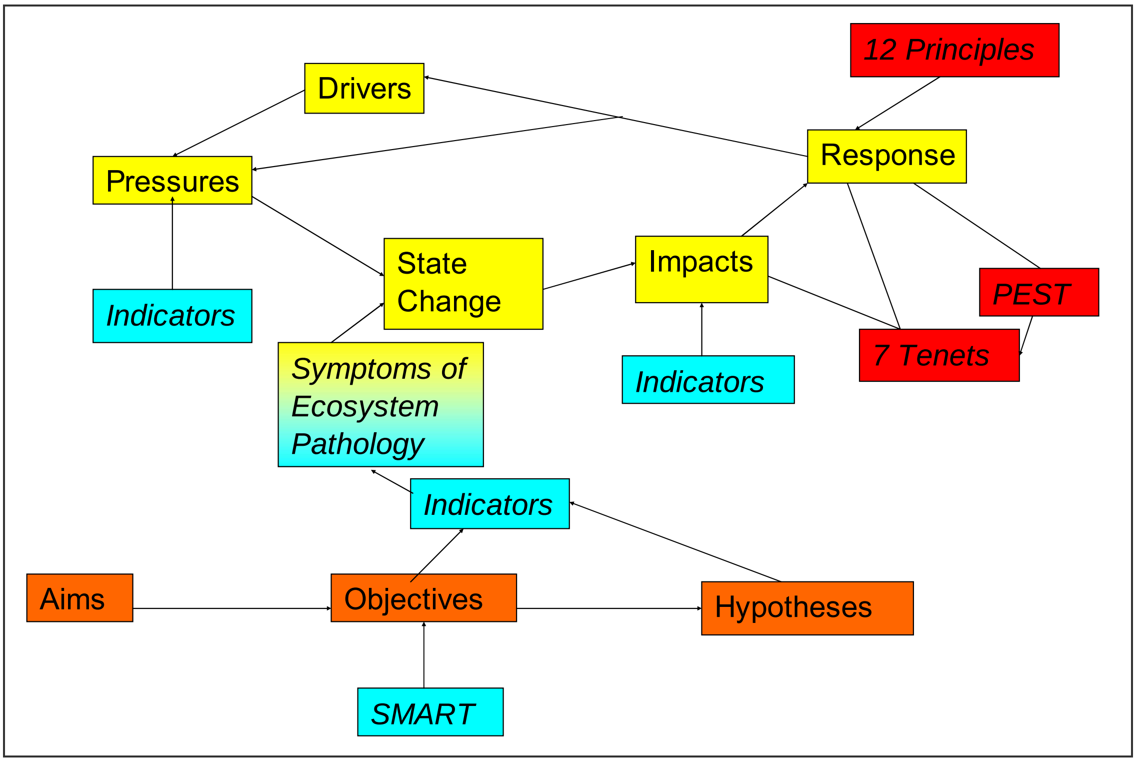


**Figure 8: A conceptual model illustrating the basis of the Ecosystem Approach in which (i) the human uses of the marine systems, their effects and societal responses are given by the DPSIR philosophy, (ii) the determination of causes of change and responses by the natural and human system requires quantitative indicators linked to monitoring and management, (iii) that the process requires good science based on the stating of objectives for the marine system and testing of hypotheses, and (iv) the overall responses to achieve a sustainable marine system requires the integration of environmental, technological and societal (administrative, political, economical and legislative) aspects as shown by the principles of the Ecosystem Approach and the PEST and 7-Tenet philosophies.**

**Table 21: Relationships between the 12 principles of the ecosystem approach and the 7 tenets of environmental management (E = explicit, I = implicit)**

| | Env. | Econ. | Tech. | Soc. | Leg. | Admin. | Polit. |
|---|---|---|---|---|---|---|---|
| Societal choices | | I | | E | | | E |
| Subsidiarity | | | | | E | E | I |
| Inter-ecosystem effects | E | | E | | I | I | I |
| Economic management | | E | I | | | | E |
| Maintain ecosystem services | E | E | I | I | | | |
| Maintain ecosystem functioning | E | | | | | | |
| Appropriate spatial and temporal scales | E | | | | I | I | |
| Long-term management | E | | | I | | I | I |
| Manage for variability | E | | | | | | |
| Manage to conserve and use biodiversity | E | E | | E | | | I |
| Use best practice, all 'data' | E | E | E | | | | |
| Stakeholder input, incl. science | E | E | E | E | E | E | E |

As an example of these concepts, and linked to the earlier part of this report, habitat restoration and re-creation can be used to illustrate this framework. Managed realignment is being carried out in many countries with the result of restoring wetland and saltmarsh habitats but the primary reason is for socio-economic benefits - the increase in public safety from the threat of coastal flooding, partly caused by sea level rise, and also for economic reasons, to reduce the cost in increasing the height of dykes. Hence, management realignment is regarded as a '*win-win-win situation*' (Edwards & Winn, 2006). The legislation provided by the Habitat Regulations, coastal defence and flood risk strategies, and Environmental Impact Assessments, amongst others, allow the managed realignment to be carried out and society is agreeable for it to happen (or at least are tolerating it) (Yozzo *et al.*, 2000). There is an administrative background provided by the environment ministries and government departments, the environment protection agencies and the nature conservation bodies to enable it to be carried out. Finally, there are the techniques, expertise and technologies, such as dyke breaching and accretion encouragement, to allow it to be achieved.

The socio-economic considerations are becoming increasingly important in effecting environmental management in getting acceptance by society and a higher prioritisation by politicians, policy makers and environmental managers. There are techniques for determining the economic costs and benefits of environmental degradation and thus improvements although these are more well-established for estuarine and coastal areas (Atkins & Burdon, 2006). The Contingent Valuation methodology and willingness-to-pay techniques allow a value to be placed on the actual and perceived damage to the environment. This then allows the cost of restoration to be justified. For example, Atkins and Burdon (2006) assessed the economic repercussions of eutrophication in a fjordic area, the societal perception of the problem and the public's willingness-to-pay for its remediation. These calculations then help to justify not only the cost of new technology (treatment plans) and farming practices aimed at reducing the problem, but also the efficacy of the policies taken such as the adoption of the EU Nitrates Directive.

The political links to ecology in achieving sustainable management which is accepted by society has recently been defined as 'political ecology' by Peterson (2000). This discipline aims to combine the fields of ecology and political economy, which together represent a constantly changing interaction between natural and anthropogenic change, and which is influenced by many stakeholders and from local to international scales. Hence, there is the need to integrate the scales at which ecosystems operate with the scales at which society operates and thus which can be used to manage systems. For example, the scale used in the management of salmon populations has to accord with the scale of their biology, i.e. it has to encompass catchment, estuary, coastal and open sea domains (Elliott & Hemingway, 2002; Peterson, 2000).

# 5. FINAL DISCUSSION, RECOMMENDATIONS AND CONCLUSIONS

## Ecosystem Understanding and Change

The management of the marine environment requires an understanding of the fundamental links between the influences of the physico-chemical environment on the biota, the biological inter-relationships at all levels from the cell to the ecosystem, and the influence of the biota on the environment, for example the structural bioengineers such as seagrasses and biogenic reef organisms. Finally, it requires a good conceptual and quantitative understanding of the way in which the system responds to stressors (e.g. McLusky & Elliott, 2004). It is emphasised here that our ability to interpret and predict the changes to the biota, both natural and human mediated, is only as good as our understanding of the way in which the physico-chemical system operates. This understanding is good for transitional and coastal environments but, as shown here, we have a limited quantitative understanding of processes especially within open marine systems. This is despite the fact that the critical marine processes can be defined as given here.

The present report has indicated that whereas many ecological concepts are well understood, for example, the nature of ecosystem structure and functioning, others such as ecological carrying capacity, resilience, and ecosystem goods and services have been defined but are still poorly quantified. Although the biodiversity of the system and the ecosystem functioning can both be measured, there is continued debate and uncertainty regarding the links between these two attributes in marine ecosystems and the causes and effects of losses and gains to ecological diversity. Giller *et al.* (2004) and Hawkins (2004) emphasise the need for the biodiversity and ecosystem functioning debate to be extended to open marine areas but even though experimental evidence is available, concepts identified for some systems will not apply elsewhere.

As indicated here and elsewhere, the nature of human-induced changes is known for many stressors in the marine area and there is a good understanding of changes at differing levels of biological organisation. For example, nutrient enhancement leads to a well defined set of symptoms which constitute eutrophication, organic enrichment changes communities in a well-known model, and seabed disturbance through the placement of windfarms or the extraction of aggregates, all have a good conceptual understanding. However, the ability of the marine, coastal, and estuarine environment to assimilate such changes still remains to be quantified. Similarly, the resilience of the marine system and its carrying and assimilative capacities (for carrying a given number of predators, an amount of an activity or receiving an amount of waste) remain to be further quantified. Superimposed on these features, are the overall changes due to unmanaged exogenic pressures such as climate change and sea-level rise. Similarly, although there is a large case-history of the way in which human activities affect the marine environment, its wide variability and openness make the detection of signals of anthropogenic change difficult against the background noise (inherent variability). In addition, while the action of local stressors are well known, e.g. in the Welsh coast or Irish Sea context, the impacts of the major external stressors of climate change and the introduction of alien and introduced species are poorly known. As shown here, there is expertise regarding the definition and use of objectives and indicators, especially in the coastal and estuarine areas, these require to be further developed for the open marine area.

Despite the above, the openness of the system gives benefits both to its resilience and its response. Because of the openness of the system, physical transport integrates ecosystem processes over greater scales (Hawkins, 2004). Hence the management of biodiversity in coastal, fringing, transitional and semi-enclosed systems can be at those scales whereas open marine systems require greater scales.

**Restoration**

The restoration literature emphasises the role of invertebrates and plants in restoration (as ecosystem engineers), the responses of fishes and higher vertebrates, and vertebrate re-introductions. It shows 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. For example, Fonseca *et al.* (2002) indicate the type of null hypotheses which could be tested, e.g. 'recovery of functional attributes can be forecast based on seagrass biomass and density alone'. In addition, there are several aspects which still require testing 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; Zedler & Adam, 2002). The science is needed to check this assumption.

The cost-benefit assessment of restoration is also required. For example, Holl and Cairns (2002) suggest that the cost of restoration is at least an order of magnitude greater than the cost of prevention. Hence there is the need for socio-economic assessments to link with the natural science to determine the value of restoration across various scales and to allow the results of localised actions to be extrapolated or otherwise the larger areas. In particular, there is the need for further studies which will quantify the chances of success and the benefits of restoration, for example:

1. the derivation of appropriate metrics to indicate restoration success;
2. an evaluation of lost resources;
3. the derivation of appropriate selection criteria for compensatory sites;
4. accurate project cost estimates and a true and complete cost-benefit appraisal which integrates economic and environmental costs and benefits; and
5. the determination of the role of disturbance as a fundamental ecological process which influences the success of restoration (modified from Fonseca *et al.*, 2002).

The restoration of terrestrial and freshwater systems has a long history and experience from which the marine system can learn. As shown by Perrow and Davy (2002), there are many successful restoration practices in the non-marine fields but because of its different nature of degradation and open characteristics, many of these may not be successful. Based on, and adapted from Hobbs (2002), there are several steps required for coastal and marine habitat and ecosystem scale management and restoration:

1. Identify the cause of the problem, for instance:

    (a) changes in biotic and/or environmental structure and functioning (e.g. assemblage types, hydrography, substratum, species loss or decline, invasion; fragmentation of habitat);

(b) changes in fluxes of physical, chemical and biological materials (e.g. species movement, water and/or nutrient fluxes);

(c) changes in the aesthetic or amenity value (e.g. actual or perceived perception of a reduction in quality);

(d) changes to existing and historical management regimes.

2. Determine realistic goals for restoration, for instance:

(a) retention of existing biota, habitat extent, underlying structure, etc. and prevention of further loss;

(b) removal of the stressor, coupled with slowing or reversal of processes or practices causing degradation;

(c) maintenance or improvement of the potential for biological production, carrying capacity and ecosystem goods and services;

(d) integration of approaches for the sustainable use and management of near and far fields.

3. Develop cost-effective planning and management tools for achieving agreed goals:

(a) determining priorities for action for different single stressors and for stressors in combination and/or with cumulative effects, in different habitat types and conditions;

(b) spatially and temporally defined solutions and management actions;

(c) acceptance and ‘ownership’ of the problems and solutions by the different stakeholders;

(d) an adaptive approach with feedback into management and which allows changes to actions when necessary.

The need for habitat restoration in coastal areas, especially those subjected to intensive agriculture, urbanisation, and tourism has increased with the large loss of habitats and therefore adverse ecological impacts (Madgwick & Jones, 2002). These are:

- 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;
- reductions in the ability of naturally functioning ecosystems to provide economically important goods and services such as erosion protection, nutrient reduction, or carbon retention (modified and expanded from Madgwick & Jones, 2002).

As is emphasised in the present report, there is most experience of restoration on sheltered and fringing habitats - saltmarshes, beaches, estuaries, and on structural components - seagrasses, biogenic reefs. This experience has reinforced the conclusions made here and by others such as Hawkins (loc. cit.) that in the open marine area, the most appropriate management action is to allow (passive) recovery after preventing the activity which first caused the degradation.

**Management**

This report has indicated the essence of The Ecosystem Approach in the need to integrate ecological aspects within a social, political, administrative, and legislative framework. Perhaps the most important management consideration is the ability to protect the carrying capacity not only in ecological terms but also in societal terms, and to aim for a wise and sustainable use of the marine, coastal, and estuarine environment. The ecosystems discussed here have differing abilities to absorb the effects of human pressures, for example a large system such as the open sea can absorb or assimilate more activities or discharges than a semi-enclosed area, but there needs to be better means of quantifying this capacity. Carter (1989) suggests that 'the carrying capacity of dune grassland is many orders of magnitude below that of rock cliffs' but it is unlikely whether that difference can be quantified further.

This discussion has indicated that the causes of many stresses in the marine environment such as discharge of materials, and the removal of aggregates and fishes can be solved and management is in place to reduce the effect of those stressors. In contrast, other more intractable problems occur such as the effects of global climate change and the introduction of alien and invasive species. For the latter, only the consequences can be managed rather than the causes, for example, on the scale at which marine management occurs, the response to sea level rise by employing managed realignment.

As discussed by MacLeod and Cooper (2005), the carrying capacities of the marine, coastal and estuarine environments, in physical, ecological, social, and economic terms, are not fixed, and can be altered by management and/or wider environmental changes. For example, provision of more facilities on the coast provides more recreation opportunities, or sea temperature rise may increase some ecological carrying capacity by allowing more species to migrate into an area or decrease it by adversely affecting breeding success of northern species. The main question remains whether the different carrying capacities are able to be maximised given their mutual incompatibility, i.e. economic carrying capacity may not be increased without a decrease in ecological carrying capacity.

The linking between the ecological concepts and the management framework is also relatively recent although, as shown here, the concepts are now being integrated to give an holistic approach to understanding, manipulating, and managing the marine environment. The growing realisation that sustainable solutions to environmental problems require the political, socio-economic, and other societal considerations to play as large if not a larger part than the ecological ones. In particular, this aspect is emphasised in the field of political ecology (Peterson, 2000).

Much has been written on the public, societal role in restoration and management (e.g. Hannam & Cochrane, 2002) and whereas this is applicable and successful for terrestrial and freshwater systems, it is relevant for estuaries but less so for coastal systems, and very little for open marine systems. This was shown by Livingston (2006) who concluded that based on many years experience, ‘citizen-orientated restoration’ such as pollution control programmes has had a major impact on the recovery of wetland systems. This also reinforces the point that fringing and transitional waters are amenable to restoration whereas open systems are not. Hence, the effort is required in preventing or controlling damaging activities and allowing natural recovery processes to occur.

Based on Hannam and Cochrane (2002) and Australia (1996), and modified from land-based systems, there are administrative and legislative changes required to produce an improved framework allowing restoration and greater marine management to occur (see below). However, whereas these will apply more easily to coastal and inland systems, they are more difficult for open marine areas. Despite this, it is expected that this framework will develop rapidly in the near future in the UK with the advent of the Marine Bill and the implementation of the EU Marine Strategy and proposed Marine Framework Directive. The changes required are:

- better administrative links allowing stakeholders (government and statutory bodies, landowners for the coastal hinterland and the community) to work together to achieve ecological restoration by sharing responsibility;
- the development of policy, guidelines, objectives and ecological standards, land and seabed use codes of practice, and indicators of the ecological limits of habitat use;
- mechanisms to allow sustainable ecological restoration to be achieved through a combination of statutory mechanisms and agreements, incentives for restoration and compensation, and the implementation of good scientific advice;
- control of unsustainable land/seabed use practices and better enforcement of existing controls (see Boyes *et al.*, 2003a-d);
- the integration of conservation and management objectives of natural resources;
- the better definition of biodiversity and ecological objectives and the better protection of their features;
- a better geographic perspective to ecological restoration including development of national, regional, and local biogeographic plans, including zonation schemes and marine spatial planning.

This report has emphasised the need for a well-defined sequence leading to marine monitoring and management. The sequence can be summarised:

(1) The definition of marine, coastal, and estuarine objectives for sustainable uses and users;

(2) The use of a marine spatial planning framework which sets the objectives into a spatial and temporal context;

(3) The derivation of quantitative indicators which, if met, act as surrogates for the wider health of the marine environment, as shown by the objectives;

(4) The determination of monitoring strategies to determine compliance with those indicators;

(5) The definition, prior to this sequence, of actions which will be taken in the case of non-compliance;

(6) Ensuring that there is the legislative and administrative support for the marine management;

(7) Ensuring the societal and economic justification and acceptance of marine management.

Each of the steps in this sequence requires further development although that development is currently occurring through a suite of existing projects being carried out for various agencies throughout the UK. However, there is the underlying need to harmonise approaches across the various regulatory frameworks, for example the definition of Good Ecological Status, Favourable Conservation Status, and Good Environmental Status respectively for the Water Framework, Habitats and Species, and proposed Marine Framework European Directives. These will be increasing challenges for the next few decades and so these aspects require to be explored in a Welsh context.

While this report has given the generic aspects relative to all marine areas, each of the aspects discussed requires further consideration in relation to the particular pressures and impacts along the Welsh coast and the offshore Irish Sea area. The present project has identified options for restoring various types of habitat and area but a cataloguing of the Welsh coastline and sea area with regard to the degraded status of the habitats was not possible within the project. A future cataloguing of this type will both put into perspective the need for restoration and identify the precise approach for each area.

There is an excellent background of information to link these aspects, such as the WFD Pressures and Impacts assessment carried out by the Environment Agency, The Environment Agency's Marine Strategy, the Marine Landscapes and biotope delimitation carried out by CCW, the shore SAC cataloguing carried out by CCW, the Marine Spatial Planning project carried out for Defra, and the marine zoning project carried out by IECS for the Irish Sea Pilot project. These data and information will allow an analysis at relevant biogeomorphic units for Welsh marine waters. Similarly, while the suite of objectives and indicators has not yet been derived for Welsh waters, this will occur as the result of projects considering the whole of the UK Continental Shelf. These sources of information will allow the mapping of management options to be superimposed on the maps of dominant processes and impacts. However, such a linking and holistic cataloguing is outwith the scope of the present project.

Finally, the present project has centred on providing knowledge of the transition from an ecosystem approach to The Ecosystem Approach, a structured approach which takes a wide view of marine characteristics, structural and functioning attributes, and ecological and societal responses to anthropogenic stressors. The report shows the complexity both of the science of the marine system and the management required for it but indicates that there is a good understanding of these aspects. Furthermore, it emphasises that the bodies within Wales have a wealth of information suitable for implementing the Ecosystem Approach. The prevailing marine governance, as legislative and administrative aspects, at regional, national, European, and international levels, will also allow an holistic approach but will require the government and statutory bodies to be familiar with marine environmental management not only in ecological terms but also in societal ones.

## GLOSSARY

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| **Abiotic** | a non-living component of an ecosystem e.g. sunlight. |
| **Active Recovery** | the human-induced response to a degraded environment. |
| **Adaptation** | the processes or coping strategies by which communities (or individuals or populations) increase their resilience (decrease their vulnerability) to ecosystem changes. |
| **Biodiversity** | the sum total and extent of genetic, taxonomic and ecological components over all spatial and temporal scales. |
| **Biogeomorphic Unit** | a geomorphic unit with recognisable biological characteristics such as an estuary, seagrass bed or a sandy beach. |
| **Biotic** | a living component of an ecosystem e.g. animals, plants, bacteria etc. |
| **Carrying/ Assimilative Capacity** | can be defined in terms of both environmental and societal demands i.e. what the natural system wants and can accommodate and what are society's aspirations; 'the maximal population (and/or community) that can be supported by the area's resources, principally space, food, and reproductive partners'. |
| **Coastal Habitat Management Plans (CHaMPS)** | in the UK, CHaMPS are non statutory plans which identify potential future changes to coastal habitats and potential compensation measures for any losses. |
| **Code of Responsible Fisheries** | a code of conduct established in 1995 by the F.A.O. in order to promote long-term sustainable fisheries. |
| **Common Fisheries Policy** | the European Union has a Common Fisheries Policy in order to manage fisheries for the benefit of both fishing communities and consumers. |
| **Compensation** | to make up or make amends for damage; the users, resource or habitat can be compensated. |
| **Compliance or Operational Monitoring** | the monitoring required to detect that a licence, authorisation, permit of consent or other adopted threshold has been met; it implies that a predefined action will be taken for non-compliance, e.g. legal proceedings may be brought. |
| **Convention on Biological Diversity** | signed by 150 government leaders at the 1992 Rio Earth Summit, the Convention on Biological Diversity is dedicated to promoting sustainable development. Conceived as a practical tool for translating the principles of Agenda 21 into reality, the Convention recognizes that '*biological diversity is about more than plants, animals and micro organisms and their ecosystems – it is about people and our need for food security, medicines, fresh air and water, shelter, and a clean and healthy environment in which to live*'. |
| **Countryside and Rights of Way Act** | in the UK, the Countryside and Rights of Way Act , 2000 gives power to the courts to require a landowner who has damaged a SSSI to restore the land to its former condition. |
| **Diagnostic or Investigative Monitoring** | also called applied research, is required to determine the cause of any change in the environment e.g. to investigate why fish no longer migrate through a particular estuary. |
| **DPSIR Approach** | identifies 'Drivers' of change leading to individual 'Pressures' causing 'State change' in the marine system. In turn, these lead to 'Impacts' on the human system which then require a 'Response' under which the problems or |

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| | potential problems are addressed. |
| **Ecological Footprint** | the area required for or affected by a human activity, such as food production or infrastructure occupation. |
| **Ecological Niche** | the ecological resource occupied by a species in a community or ecosystem. |
| **Ecological Range** | refers to the overall geographical area covered by the species. |
| **Economic Carrying Capacity** | refers to the extent to which an area can become changed before the economic goods and services are adversely affected. |
| **Ecosystem** | a dynamic complex of plants, animals and micro-organisms and their environment interacting as a functional unit. |
| **Ecosystem Approach** | can be regarded as a philosophy for summarising the means by which the natural functioning of an ecosystem can be protected and maintained while still allowing and delivering sustainable use and development by society. |
| **Ecosystem Capital** | any asset or stock of assets from an ecosystem that is capable of producing an income. |
| **Ecosystem Condition (Health)** | a healthy ecosystem can be described as a system that functions well and has the capability to resist, or recover from, disturbance. |
| **Ecosystem Functioning** | describes those components involving rate processes, i.e. changes in any component with time and may be regarded as the sum total of all the processes which occur within the system. |
| **Ecosystem Goods and Services** | in anthropocentric terms the fauna and flora provide commodities or goods, such as fish, shellfish and alginates, as well as services such as water cleansing and purification and enhancement of tourism. |
| **Ecosystem Processes** | implies the incorporation of a rate change, i.e. a feature of the system that changes with time. |
| **Ecosystem Resilience** | the ability of an ecosystem to return to its original state after being disturbed. |
| **Ecosystem Structure** | the composition of the biological community including species, numbers, biomass, life history and distribution in space of populations; the quantity and distribution of the abiotic (non-living) materials such as nutrients, water, etc; the range, or gradient, of conditions of existence such as temperature, light etc. |
| **Environmental Impact Assessment Directive** | Council Directive 85/337/EEC of 27 June 1985 on the assessment of the effects of certain public and private projects on the environment which was amended in 1997. The Directive requires member states to put into place procedures for the EIA of certain public or private projects, before they are authorised in order to ensure that all projects that are likely to have significant environmental effects are assessed. |
| **Environmental Liability Directive** | Council Directive 2004/35/EC of 21 April 2004 on environmental liability with regard the prevention and remedying of environmental damage. The Directive requires member states to apply the ‘pollluter pays principle' so that those causing damage to the environment are legally and financially responsible for that damage. |
| **Euryhaline** | of or relating to the capability of an organism to live in environments of variable salinity. |
| **Favourable Conservation Status** | the status of a designated habitat or species under the EU Habitats directive which ensures its fitness for purpose (range, structure and function) or survival/viability, respectively. |

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| **Functional Groups** | a combination of species with similar ecological characteristics e.g. wading birds. |
| **Good Ecological Status** | the status of a biological element as defined under the normative definitions of the EU Water Framework Directive in showing only a slight deviation from High Ecological Status. |
| **Good Environmental Status** | the status of a marine habitat under the proposed EU Marine Framework Directive and showing little deviation from a reference, unimpacted condition (still to be formally defined). |
| **Habitat Creation** | an anthropogenic intervention which produces a habitat not previously present. |
| **Habitat Enhancement** | a management approach which directly or indirectly results in an increase in ecological value of the habitat, for example increased numbers of over-wintering wading birds on an estuary. |
| **Habitat Occupation** | refers to the different physical areas in which an organism can occur. |
| **Habitats Directive** | Council Directive 92/43/EEC of 21 May 1992 on the conservation of Natural Habitats and of Wild Flora and Fauna. This Directive requires measures to be taken to maintain or restore to favourable conservation status in their natural range, habitats and species of flora and fauna of Community Interest and listed in Annexes to the Directive. It provides for a European-wide ecological network of **Special Areas of Conservation (SACs)**. |
| **Habitats Regulations** | Conservation (Natural Habitats &c.) Regulations, 1994 are used to transpose the **Habitats Directive** into UK national legislation. |
| **Integrated Pollution Prevention and Control Directive** | Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control. This Directive requires member states to prevent, or when that is not practicable, to reduce emissions to air and water in order to achieve a high level of protection of the environment as a whole. |
| **Levels of Biological Organisation** | structure and functioning occurs at various levels of organisation for example cell, individual, population, community, ecosystem. |
| **Managed Realignment** | is a modern management option where wetlands are created either as water storage areas to combat flooding or at flood defence areas to combat sea-level rise, erosion and/or land sinking. |
| **Marine Strategy** | is aimed at protecting Europe's seas and oceans and ensuring that human activities in these seas and oceans are carried out in a sustainable manner so that we and future generations can enjoy and benefit from biologically diverse and dynamic oceans and seas that are safe, clean, healthy and productive. |
| **Marine Strategy Framework Directive (proposed)** | this proposed Directive requires the achievement of Good Environmental Status based on deviation from a reference condition. |
| **Mitigation** | the act of making any impact less severe. |
| **Natura 2000** | European-wide ecological network made up of SACs and SPAs. Measures for managing Natura 2000 sites are given in Article 6 of the **Habitats Directive**. |
| **Niche Breadth** | can be regarded as combining **Habitat Occupation** and **Ecological Range**. |
| **Niche Complementarity** | occurs where organisms have non-overlapping but complementary niches. |
| **Niche Overlap** | occurs when two organisms require the same conditions, food type, etc. and |

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| | as such may lead to competition between species (interspecific) or within a species (intraspecific); the competition can then be minimised by niche separation in space or time. |
| **Nitrates Directive** | Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. This Directive requires member states to reduce water pollution caused or induced by nitrates from agricultural sources and to prevent further pollution of this type. |
| **OSPAR Convention** | a political agreement formed, following the amalgamation of the Oslo and Paris conventions, and which aims to protect the marine environment of the North-East Atlantic. |
| **PEST Analysis** | analysis in which the organisation of an environment can be analysed against a background of its ***P****olitical,* ***E****conomical,* ***S****ocial and* ***T****echnological* environment. |
| **Physical Carrying Capacity** | refers to space limitations, i.e. the number of activities an area can withstand before there is some change to quality. |
| **Polluter Pays Principle** | requires that those causing damage to the environment (water, land, and nature) are legally and financially responsible for that damage. |
| **Propagules** | any part of an organism capable of independent growth, usually from a dispersal stage. |
| **Ramsar Convention** | 1971 Convention on Wetlands of International Importance. An intergovernmental treaty which provides the framework for national action and international co-operation for the conservation and wise use of wetlands and their resources. |
| **Reclamation** | implies not necessarily a return of an ecosystem to an original state but merely making an area fit for purpose or required use. |
| **Recoverability** | the ability of a habitat, community or individual (or individual colony) of species to redress damage sustained as a result of an external factor. |
| **Re-creation** | this term 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 system. |
| **Re-establishment** | indicates the replacement of a structural component of the ecosystem in sufficient quantities to allow it to regain its overall nature and thus restore the ecological functioning. |
| **Rehabilitation** | the act of partially or, more rarely, fully replacing structural or functional characteristics of an ecosystem, that have been diminished or lost, or 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. |
| **Re-introduction** | indicates actively placing a species back into an area where it was once present. |
| **Remediation** | action taken at a site following anthropogenic disturbance to restore or enhance its ecological value. |
| **Replacement** | may be implied if the new area has a use different from that originally or when being degraded. |
| **Resource Partitioning** | the division of resources such that a few dominant species exploit most of the available resources while other species divide the remainder |

**Restoration** can be defined as the return of a coastal habitat from a disturbed or totally altered condition to a previously existing natural condition, or altered condition, by man.

**Seven Tenets** there is the requirement today to satisfy all 7 tenets for successful environmental management, i.e. to ensure that management options are environmentally sustainable, technologically feasible, economically viable, socially desirable, legally permissible, administratively achievable and politically expedient.

**Shoreline Management Plans (SMPs)** within the UK, an SMP provides a large-scale assessment of the risks associated with coastal processes and presents a long term policy framework to reduce these risks to people and the developed, historic and natural environment in a sustainable manner.

**Size / Biomass Spectra** plots the relationship between the size of an organism and its biomass.

**SMART Objectives** in order to determine if the objectives have been met, they should be SMART (Specific, Measurable, Achievable, Realistic and Time-bounded) thus resembling quantitative indicators.

**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.

**Special Area of Conservation** see **Habitats Directive**.

**Stenohaline** tolerant of only a narrow range of salinities.

**Strategic Environmental Assessment Directive** Council Directive 2001/42/EC of 27 June 2001 on the assessment of the effects of certain plans or programmes on the environment. The Directive requires that an environmental assessment is carried out and that the results are taken into account during the preparation and adoption of such plans and programmes.

**Substratum** material available for colonization by plants and animals.

**Surveillance or Condition Monitoring** previously called surveillance, is the act of sampling, possibly on a repeated basis and with good spatial coverage, a feature or features.

**Symptoms of Ecosystem Pathology** a few well-defined categories of changes to ecosystems as the result of human activities i.e. adverse changes to the system.

**Taxonomic Approach** an approach in which all species are identified and the patterns between those species are determined.

**UK Biodiversity Action Plan** places duty on UK government Ministers to have regard to the purposes of biodiversity conservation in accordance with the **Convention on Biological Diversity**.

**Water Column** a vertical expanse of sea water stretching from the ocean surface to just above the ocean floor.

**Water Framework Directive** Council Directive 2000/60/EC of 23 October 2000 on the framework for the Community action in the field of water policy. The Water Framework Directive expands the scope of water protection to all waters and sets a clear objectives that ‘good status’ must be achieved for all European waters by 2015 and that sustainable water use is ensured throughout Europe.

**Welsh Waters** defined as the waters adjacent to Wales extending out to 12 nm from the median line down the Dee estuary in the north to the median line down the Severn estuary in the south.

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| **Wild Birds Directive** | Council Directive 79/409/EEC of 2 April 1979 on the Conservation of Wild Birds. This Directive aims to protect bird species within the European Union through the conservation of populations of certain birds and the habitats used by these species. States are required to classify **Special Protection Areas (SPAs)** to conserve the habitats of rare and vulnerable species listed in Annex 1 of the Directive, and of regularly occurring migratory species, to ensure their survival and reproduction in their area of distribution. |
| **Wildlife & Countryside Act** | the Wildlife and Countryside Act, 1981 is the principle mechanism for the legislative protection of wildlife in Great Britain, and as such allows UK courts to require a landowner who has damaged a SSSI to restore the land to its former condition. |

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