The following supplements accompany the article

Framework for understanding marine ecosystem health

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SUPPLEMENT 1. LEGISLATION AND ECOSYSTEM HEALTH

The need to observe and manage the state of ecosystems as a whole is recognized in the 'Ecosystem Approach' and the marine environmental protection laws of several states. Table S1 contains extracts from some relevant documents, emphasizing phrases requiring or emphasizing an integrated or holistic approach.

Table S1. Some details of the 'Ecosystem Approach' and related 'Ocean Policies'. Words implying an integrated, i.e. holistic, approach (to ecosystems) have been underlined

Source	Extract
Selected principles of the **Ecosystem Approach** updated (SCBD, 2012) from those accepted at the Earth Summit in Rio in 1992	3: Ecosystem managers should consider the effects ... of their activities on adjacent and other ecosystems. 5: Conservation of ecosystem structure and functioning, in order to maintain ecosystem services .... functioning and resilience depends on a dynamic relationship within species, among species and between species and their abiotic environment, as well as the physical and chemical interactions within the environment. 7: The ecosystem approach should be undertaken at the appropriate spatial and temporal scales. Boundaries for management will be defined operationally ... The ... approach is based upon the hierarchical nature of biological diversity characterized by the interaction and integration of genes, species and ecosystems. 8: ... objectives for ecosystem management should be set for the long term. 9: Management must recognize the change is inevitable. 10: ... seek the appropriate balance between, and integration of, conservation and use of biological diversity.
Australia's Oceans Policy of 1998, according to IOC (2007)	[A] framework for integrated and ecosystem-based planning and management of all of Australia's marine jurisdictions. Its vision is of 'healthy oceans, cared for and used wisely for the benefit of all, now and in the future'.
White Paper of 1998 on the Development of **China**'s Marine Programmes, from IOC (2007)	The basic objective of comprehensive marine management is to ensure a healthy marine environment and the sustainable utilization of marine resources.
European Water Framework Directive (EC 2000)	… policy on the environment is to contribute to pursuit of the objectives of preserving, protecting and improving the quality of the environment, in prudent and rational utilisation of natural resources; aims to achieve good ecological status, defined (Annex V) as that of a (fresh or salt) water body in which conditions deviate only slightly from those normally associated with the surface water body type under undisturbed conditions; 'ecological status' (article 2.21) is an expression of the quality of the structure and functioning of aquatic ecosystem, defined (for coastal waters) by 'biological elements' for phytoplankton, 'other aquatic flora' and 'benthic invertebrates', and supporting hydromorphological and physico-chemical elements.
European Marine Strategy Framework Directive (EC 2008)	'... apply an ecosystem-based approach to the management of human activities, ensuring that the collective pressure of such activities is kept within levels compatible with the achievement of good environmental status ... [which (article 3.5)] means the ... status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive within their intrinsic conditions, and the use of the marine environment is at a level that is sustainable … [and] the structure, functions and processes of the constituent marine ecosystems ... allow those ecosystems to function fully and to maintain their resilience to human-induced environmental change'; good status is to be assessed using 11 'Qualitative Descriptors' including requirements for (1) maintenance of biodiversity, (3) healthy stocks of exploited fish and shellfish, (4) normal structure of food webs, (5) minimal eutrophication, (6) protection of seafloor integrity.
COM (2010) Annex part A	'(3) ... it is important that assessment considers the main cumulative and synergetic effects of impacts on the marine ecosystem ...'
USA Oceans Act of 2000, according to IOC (2007)	established a commission which proposed (2004) a 'move toward an ecosystem-based management approach'.

SUPPLEMENT 2. SYMPTOMS OF ECOSYSTEM PATHOLOGY

Elliott (2011) described 'ecosystem health' as providing protection against the 'ecosystem pathologies' of Harding (1992) and McLusky & Elliott (2004) that are listed in Table S2. Odum (1985) listed trends expected in 'stressed ecosystems' (Table S3), basing these on a conceptual model of ecosystem succession under undisturbed conditions (Odum 1969). These 2 sets of illhealth diagnostics were used as the basis for the *empirical* (aggregatable) criteria for marine ecosystem health in Table 1 in the main text. (See glossary in main text for explanations of italicised terms.)

Table S2. Seven indicators of ecosystem pathology (modified from Harding 1992 by McLusky & Elliott 2004)

Category	**Symptoms**
Primary production:	the organic production of a system which may be overstimulated through increased sewage inputs;
Nutrients (fate & effects):	the increase in concentration as the result of increased diffuse and point source discharges but also as the cause of eutrophication;
Species diversity **(abiotic areas):**	the removal of species which are intolerant of change under stressful conditions and the encouragement of tolerant species;
Community instability **(biotic composition)**:	the increase in biological turnover due to the dynamics of stress-tolerant species;
Size and biomass spectrum:	the tendency towards smaller, r-strategist organisms under stressed conditions;
Disease/anomaly prevalence:	the reduced tolerance of organisms to infection and pathological anomalies under stress;
Contaminant uptake and response:	the increased accumulation of conservative contaminants and perhaps the production of detoxification mechanisms after exposure.

Table S3. Trends expected in stressed ecosystems: those experiencing 'a disorganizing or detrimental influence' (Odum 1985)

Category	**Trend**
Energetics	1. Community respiration increases 2. Ratio of production to respiration becomes unbalanced 3. Ratios of production and respiration to biomass increase 4. Importance of auxiliary energy production increases 5. Exported or unused primary production increases
Nutrient cycling	6. Nutrient turnover increases 7. Horizontal transports increase and vertical cycling decreases 8. Nutrient losses from system increases
Community structure	9. Proportion of *r-strategeists* increases 10. Size of organisms decreases 11. Lifespan of organisms or parts decreases 12. Food chains shorten (because of reduced energy flow to higher levels or greater sensitivity of predators to stress) 13. Species diversity decreases and dominance increases (if original diversity is low, reverse may occur); redundancy of parallel ecosystem processes decreases
General, system-level, trends	14. Ecosystem becomes more open (i.e. input and output [environments] become more important as internal cycling is reduced) 15. Autogenic succession trends reverse (succession reverts to earlier stages) 16. Efficiency of resource use decreases 17. Parasitism and other negative interactions increase, and mutualism and other positive interactions decrease 18. Functional properties (such as community metabolism) are more robust (homeostatic – resistant to stressors) than are species composition and structural properties

Supplement 3. ECOSYSTEM ORGANIZATION

Costanza (1992) reached a definition of ecosystem health as 'a comprehensive, multiscale, dynamic, hierarchical measure of system *resilience*, *organization*, and *vigor*' on the basis of a review that is summarized in Table S4. As discussed in our main text, *biodiversity* is a component of ecosystem organization, but the relationship between it and ecosystem functioning is not simple, and has been much debated. Table S5, drawn from Hooper et al. (2005) lists statements that can be made about this relationship with comparatively high confidence. Their sources refer mainly to terrestrial communities.

Table S4. Costanza's (1992) 'Concept definitions of ecosystem health'

Health as ...	Expansion and Discussion **(Costanza)**	Comments **(authors)**
... homeostasis	'... any and all changes in the system ... [measured by change] in any indicator beyond the range of 'normal variation' ... represent a decrease in health.' But it is difficult to define a normal range for ecosystems, of which there are small populations. Furthermore, nature is in a constant state of change, and not all change is bad.	Homoeostasis is 'the tendency towards a relatively stable equilibrium between interdependent elements' (Concise Oxford Dictionary).
... the absence of disease	Requires definition of disease, which can lead to circular arguments. Perhaps 'a perturbation [of the system] with ... a specific cause and characteristic symptoms ... [i.e.] certain negative effects. ... but without an independent definition of health it is impossible to know which ... stresses really cause problems (are negative versus positive) and to what degree.'	Costanza's argument is that health is more than absence of known diseases. His use of the word 'stress' sometimes implies external pressure on the system, sometimes a disease in the system.
... diversity or complexity	'the idea is that diversity or complexity are predictors of stability or resilience and that these are measures of health. This linkage has been the subject of much controversy in the ecological literature ...'	See 'Organization and biodiversity' in main text.
... stability or resilience	'Healthy organisms have the ability to resist disease organisms. They are resilient and recover quickly after a perturbation. Hence this leads to the definition of health as the ability to recover from stress. ... [but] this definition says nothing about the system's operating level or degree of organization ... [thus] a more appealing definition of resilience is 'the ability of a system to maintain its structure and patterns of behaviour in the face of disturbance' (Holling 1986) ... [which] stresses the adaptive nature of ecosystems.'	Need to distinguish resistance to external pressures from adaption to those pressures. Some systems behave hysterically in response to pressure changes and some authors have used 'resilience' to refer to the recovery from perturbation (see Elliott et al. 2007, Tett et al. 2007). Systems that cannot resist, recover, or adapt, can survive by change, often called regime shift.
... vigor or scope for growth	It has been hypothesized that a system's ability to recover from stress ... is related to its overall metabolism or energy flow (Odum 1971) or to its 'scope for growth' (Bayne et al. 1987)	'Vigor' is related to the classical Greek concept of eudaimonia (Parry 2009) and the 'flourishing' aspect of health; it underpins resilience.
... balance between system components	It is widely accepted in Eastern traditional medicine that 'a healthy system is one that maintains the proper balance between system components. This idea of balance is deeply ingrained in ecological theory ... but has usually been used as a general explanation for existing distributions (the ecosystem is in balance) rather than in any predictive or diagnostic way.'	See Gowen et al. (2012).

Table S5. Some high-confidence conclusions (Hooper et al. 2005) concerning effects of biodiversity on ecosystem functioning, mainly in terrestrial communities

'Species' functional characteristics strongly influence ecosystem properties.'
'Alteration of biota in ecosystems via species invasions and extinctions caused by human activities has altered ecosystem goods and services in many well-documented cases.'
'The effects of species loss or changes in composition, and the mechanisms by which the effects manifest themselves, can differ among ecosystem properties, ecosystem types, and pathways of potential community change.' 'Some ecosystem properties are initially insensitive to species loss because (a) eco-systems may have multiple species that carry out similar functional roles, (b) some species may contribute relatively little to ecosystem properties, or (c) properties may be primarily controlled by abiotic environmental conditions.'
'More species are needed to insure a stable supply of ecosystem goods and services as spatial and temporal variability increases, which typically occurs as longer time periods and larger areas are considered.'
'Certain combinations of species are complementary in their patterns of resource use and can increase average rates of productivity and nutrient retention.'
'Having a range of species that respond differently to different environmental perturbations can stabilize ecosystem process rates in response to disturbances and variation in abiotic conditions.'

SUPPLEMENT 4. FUNCTIONAL DIVERSITY IN SOFT-SEDIMENT BENTHOS

Pearson & Rosenberg (1976, 1978) reported benthic response to organic enrichment both in terms of diversity indices and in a diagram showing a sequence of characteristic organisms and community structure (Gray & Elliott 2009). Glémarec & Hily (1981) categorized these organisms into 'five groups of species which present similar abundance profiles along the enrichment gradient', and Borja et al. (2000) devised a formula to combine the abundance of each group into a continuous scalar variable representing ecological quality or 'benthic community health'. The resulting AZTI Marine Biotic Index (AMBI) has been widely applied to assess anthropogenic perturbations in estuarine and coastal benthic communities (Muxika et al. 2005, Borja et al. 2011). Because the groups were defined in terms of response, they were not functionally homogenous; nevertheless, as defined by Grall & Glémarec (1997) they are distinguishable in terms of functional traits (Table S6). If their abundances are treated as state variables, the groups define a 5-dimensional state space, with AMBI a derived scalar giving distance from a healthy domain.

Table S6. Five groups of species which present similar abundance profiles along benthic enrichment gradients (Grall & Glémarec 1997 after Glémarec & Hily 1981), and leading to the groups used in the AZTI Marine Biotic Index (AMBI)[b] by Borja et al. (2000)

Group	Response to organic enrichment	Characteristic members [indicating a functional group]
I	Very sensitive species; present in *normal conditions*[a]	Specialist carnivores and some deposit- feeding tubicolous polychaetes
II	Species that are indifferent to enrichment	Suspension feeders, less selective carnivores and scavengers, present in low densities with little temporal variation
III	Tolerant of excess organic matter enrichment; may occur in normal conditions but their populations are stimulated by organic enrichment	Some of the surface-deposit-feeding species, e.g. tubicolous spionids
IV	Second order opportunistic species	Small species with a short life cycle, adapted to a life in reduced sediment where they can proliferate: the subsurface deposit feeders related to the cirratulids
V	First order opportunistic species	Deposit feeders that proliferate in sediments reduced up to the surface, especially the polychaetes *Capitella capitata* and *Scolelepis (Malacoceros) juliginosa*

[a]Muxika et al. (2005) equated these conditions with 'normal benthic community health' and with 'high' status under the EU Water Framework Directive

[b]The algorithm is: AMBI = $\sum w_i \cdot A$, where the A_i are the proportional abundances of the groups (i = I ... V), summing to 1, and the weights (*w)* are 0, 1.5, 3, 4.5, 6

SUPPLEMENT 5. OBSERVATIONAL METHODS

Methods for observing spatial and temporal variability in marine ecosystems are listed in Table S7. Such variation, if analysed in terms of ecosystem health, can be related to gradients of pressure and thus used to understand and manage the pressures that disturb health. In addition, we anticipate that the use of these methods will lead to a better understanding of the role of spatial variation in holistic ecosystem function. Some of the methods are new, and thus have been in use for insufficient time to generate the time-series needed for the method of analysing trajectories described in the main text. However, they are likely to become increasingly useful as data accumulates.

Table S7. Summary of platforms, example programmes and methodologies that might be used for assessing holistic ecosystem state and its change. See also Schiff et al. (2002). In column headings: T_{max} = typical greatest duration of existing time-series taken from cited examples, T_{res} = typical minimum time interval resolved, Span = maximum spatial extent, Grain = typical minimum spatial distance resolved, and Cost = rough estimate of annual cost of using method in power-of-10 euros: e.g. '5' = 1 – 9 × 10^5 euros

Platform (hardware & institutional arrangements)	**Method**	Measuring **(examples)**	**Selected references**	T_{max} (yr)	T_{res}	Span	Grain	**Cost**/unit.year
Orbiting satellite	Passive remote sensing	Sea colour and reflectance (e.g. plant pigments, suspended sediments)	Holligan et al. 1989, Platt & Sathyendranath 2008, Platt et al. 2010	30+	days	Regional sea, global	km	7 (for regional sea; inc. satellite cost; marginal cost = 4–5)
Ships, moorings & landers; observatories (programmes that operate these for long-term monitoring)	Automated sensors, water sampling	Physical, chemical properties, plankton, benthos	Mills et al. 2003, Harris 2010, Widdicombe et al. 2010	20	hours	Site	10 km	6 (per site or small network)
Fisheries research ships in stock assessments	Sampling eggs, larvae and adult fish	Fish demographics	Heath & Speirs 2012	80	years	Regional sea	100 km	6
Research ships in major programmes	Any	Any	Künitzer et al. 1992, Charnock et al. 1994	intermittent	hours	regional sea	km	7 (for 'North Sea Project 88–89')
Ships of opportunity	Ferrybox: automated flow-through monitors and sampler	Chlorophyll fluorescence, phytoplankton, chemical properties	Petersen et al. 2011, www..ferrybox.com/	>10	>1 day	Regional seas, global	10 nm	5
	CPR (Continuous Plankton Recorder) Survey	'Phytoplankton colour index'; (larger) phyto-plankton; zoo-plankton; micro-plastics	Colebrook 1960, Warner & Hays 1994, Batten et al. 2003a,b, Edwards et al. 2010, McQuatters-Gollop & Vermaat 2011	50+	month	Regional sea, ocean basin	10 nm	5
Autonomous underwater vehicle (AUV) programmes	Gliders, wave gliders, Remotely operated oehicles	Chlorophyll, oxygen	Curtin et al. (2005)	0	hours	Regional sea, ocean basin		5
Conservation monitoring	Stocks or condition of selected species	e.g. seabird, marine mammal variables	Wanless et al. 2007, Herman et al. 2011	40+	annual	Part of regional sea	100 km	5
Compliance monitoring	Benthic survey of at-risk and reference sites	Seabed and benthos condition	Borja et al. 2010	40+	annual	Regional sea	10 m–100 km	6 (for UK seas)
Shore based monitoring	Shellfish hygiene: water samples, shellfish toxin content	Harmful algae, toxicity	Shumway et al. 1988	50+	bi-weekly	Regional coast	10–100 km	6 (for UK waters)
	Fish landings (and effort)	Fish demographics	Thurstan & Roberts 2010	150	months	Regional sea	100 km	6

SUPPLEMENT 6. A MODEL FOR ECOSYSTEM RESILIENCE

A simple equation for ecosystem resistance to *pressure* can be derived by analogy from Hooke's Law for the elastic extension of a mechanical spring.[1] The equation is:

$$\Delta S = -c \cdot \Delta P \qquad \text{(S1)}$$

where S is a measure of ecosystem *state* or condition, and P is a measure of the (external) *pressure* on the ecosystem. ΔS and ΔP refer to changes relative to an earlier state, or a 'reference' state. The proportionality between changes in state and changes in pressure is given by *compliance*, c. This is the inverse of the resilience component *resistance*. The *latitude* is the range of states over which Eq. (1) applies for both $+\Delta P$ and $-\Delta P$, and corresponds to mechanical systems operating within their elastic limit.

In order to specify state more precisely, **S** is defined as a set of ecosystem state variables or derived indicators, averaged or summed over appropriate scales in space and time. Change in this state space is shown by a vector:

$$\vec{\mathbf{S}} \equiv \left\{\Delta S_i\right\}_{i=1}^{i=n} \equiv \left\{\Delta S_1,\cdots,\Delta S_i,\cdots,\Delta S_n\right\} \qquad \text{(S2a)}$$

Change in a pressure state space can analogously be shown as:

$$\vec{\mathbf{P}} \equiv \left\{\Delta P_j\right\}_{j=1}^{j=m} \equiv \left\{\Delta P_1,\cdots,\Delta P_j,\cdots \Delta P_m\right\} \qquad \text{(S2b)}$$

These vectors can be reduced to scalars by (1) plotting the variables on orthogonal axes, (2) approximately self-standardizing the variables by logarithmic transformation, and (3) computing the Euclidian norm of the vector. This gives the scalar relative change for state (s) and pressure (p):

$$s = \sqrt{\sum_{i=1:n}\left(\Delta \ln\left(S_i\right)\right)^2} \qquad \text{(S3a)}$$

$$p = \sqrt{\sum_{j=1:m}\left(\Delta \ln\left(P_j\right)\right)^2} \qquad \text{(S3b)}$$

Change in these scalars comprises (1) long-term components *p(t)* and $s(t) = c \cdot p(t)$ relative to reference conditions, and (2) medium-term, in our case inter-annual, components p' and s', where state *scalar variability:*

$$s' = c' \cdot p' + \varepsilon \qquad \text{(S4)}$$

and c' is the local *compliance*. Given constant distributions of medium-term pressure variability p' and ecosystem state 'noise' ε, the equation predicts $s' \propto c'$: i.e. that ecosystem state variability increases with decreasing resilience. The long term trend *s(t)* can be estimated by fitting a polynomial to the time-series of s relative to an arbitrary reference. Values of s' can be estimated as (absolute) deviations from this trend. This method allows resilience to be investigated from time-series of ecosystem states.

Compliance can be estimated from the ratios $\Delta S : \Delta P$, $\vec{\mathbf{S}} : \vec{\mathbf{P}}$, or s to p. As exemplified by the distinction between *s(t)* and s', however, compliance need not be a constant. A more general aim is therefore to parameterize the compliance function f_C in the equation:

$$\vec{\mathbf{S}} = f_c(\mathbf{S_I}, -\vec{\mathbf{P}}) \qquad \text{(S5)}$$

where $\mathbf{S_I}$ is the subset of ecosystem state variables that maintain system integrity.

[1] Robert Hooke's first explicit statement (1678) of his law was "ut tensio, sic vis": 'as the extension, so the force' (http://en.wikipedia.org/wiki/Hooke%27s_law)

SUPPLEMENT 7. PRIMARY PRODUCTION IN THE NORTHERN NORTH SEA

Pätsch & Radach (1997) concluded that observed primary production in the northern North Sea was 100 to 125 g C m^{-2} yr^{-1}. Heath & Beare (2008) calculated new production from the observed Spring draw-down in nutrients, 1960 to 2003. Their central value for waters north of 57.5°N (ICES region IVa) was 70 (90% range 52 to 95) g C m^{-2} yr^{-1}, with higher values during the first 2 decades. In contrast, the Continuous Plankton Recorder (CPR) 'Phyoplankton Colour Index', related to photosynthetic pigments, increased in the non-coastal parts of the North Sea during the late 1980s (McQuatters-Gollop et al. 2007). An earlier version of European Regional Seas Ecosystem Model (ERSEM) estimated primary production between 50 and 75 g C m^{-2} yr^{-1}, with no trend between 1955 and 1983 (Pätsch & Radach 1997). The most realistic simulations with the PROVESS Water Quality Model (PROWQM) estimated 'net microplankton primary production' as 91 (Lee et al. 2002) and 77 (Tett & Lee 2005) g C m^{-2} yr^{-1} for 1998. It is difficult to draw conclusions about the reliability of the simulated time-series, given the diversity of other estimates of production. However, the use of climatological northern boundary conditions excludes from the GETM-ERSEM time-series any interannual variability and trends that might result from changes in the Atlantic inflow to the North Sea.

SUPPLEMENT 8. RESEARCH QUESTIONS

Our review and methodological proposals raise a number of issues that might be resolved through further research. They are listed in Table S8.

Table S8. Outstanding issues relating to marine ecosystem health

	Issue involving	Broad research questions
1	Biodiversity	How meaningful and useful are the concepts of functional (trait and response) diversity? Are they crucial for resilience? Does loss or lack of functional response diversity within a functional group place that group (and ecosystem function) more at risk of elimination? Can species-poor ecosystems potentially contain as much functional diversity within a few generalist and adaptive species as species-rich systems do with high biodiversity?
2	Pressure and change	Ecosystems are open systems and resilience refers to the generic processes by which they maintain their integrity despite flows of energy and materials. How do they respond when these flows change? Are there differences in responses to human as opposed to natural causes of change? Are coastal marine ecosystems, stripped of top predators/large animals, less resistant to climate change and endogenous anthropogenic pressures?
3	Healthy versus pristine ecosystems	Is there a unique healthy condition for an ecosystem instancing a given biome, and is it the condition under minimal human pressure? Or can there be several healthy (fully-functioning) states corresponding to a particular ecohydrodynamic condition, even if the different states provide different services?
4	Granularity	Does spatial heterogeneity contribute to resilience as suggested by theories of panarchy? What areal proportion of an ecosystem needs protection from endogenous pressures to sustain good health? Is the answer different for pelagic and benthic components?
5	Choice of state variables	How many variables are optimal to characterize the health of a marine ecosystem, and what should they be? Should we accept constraints set by an existing set of monitored variables or explore what is possible with developing methodology?

6	Modelling	Can the current generation of marine ecosystem models capture system properties relating to resilience? Can current functional-group models correctly hindcast changes in coastal ecosystems, and their variability, using observed changes in pressures as drivers?
7	Variability in time	How best to observe temporal variability in ecosystems and distinguish between (1) 'noise', (2) recurrent seasonal or successional changes that are part of ecosystem *organization*, (3) variability that might be used as a proxy for (inverse) resilience (4) long-term trends due to anthropogenic and natural causes?
8	Social attitudes to ecosystem change	Can a theory of ecosystem health be based solely in natural science or must it inevitably be influenced by social norms (i.e. by what a society wishes for and from the sea)?
9	Management	How can theories of health support the *ecosystem approach* to the management of human use of marine services? How can these theories be used to manage pressures and thus avoid irreversible changes to ecosystems and their services? Should the aim be to optimize ecosystem services or reduce risks e.g. of regime shift?
10	Indicators of health	What are the proper combinatorial rules for multi-indicator (multi-metric) systems? If a state space approach with orthogonal, self-standardized axes, provides such rules automatically, what is the best way to measure 'distance travelled' in state space?

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