DETECTING *UNDESIRABLE DISTURBANCE* IN THE CONTEXT OF EUTROPHICATION

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The checklist is provided as a separate document, which should be appended to this.

Introduction

The need to define ***undesirable disturbance*** arises from the definitions of ***eutrophication*** in the Urban Waste Water Treatment Directive (UWWTD) and the Nitrates Directive, and in OSPAR's *strategy to combat eutrophication.* The three definitions are similar, and the first part of the OSPAR (2003) definition is representative:

> *"Eutrophication" means the enrichment of water by nutrients causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned...*

A water identified as suffering from ***eutrophication*** is labeled as *sensitive* under the UWWTD, *nitrate-vulnerable* under the Nitrates Directive, and a *problem area* under OSPAR's strategy. The consequences of such identification include requirements for *more stringent* treatment of urban waste water before its discharge, reduction in the use of nitrate fertilizers on land, and measures *to reduce or to eliminate the anthropogenic causes of eutrophication.* The last is an explicit requirement of OSPAR's strategy and might well be required under the Water Framework Directive (WFD). The practical implications of such measures extend far beyond particularities of sewage treatment and nitrate fertilizer use to the need to control nutrient release by agriculture, aquaculture, transport and urban development in general.

Because nutrient enrichment and accelerated algal growth are not in themselves harmful, a diagnosis of eutrophication can be properly made only when *undesirable disturbance to the balance of organisms ... and to the quality of the water* ... is demonstrated. Given the need to do this for UK salt waters, Defra commissioned a 2-stage study aimed at defining ***undesirable disturbance*** *in the context of eutrophication* and at proposing a monitoring strategy for detecting such disturbance. In stage 1 of the work (Anon, 2004a), the ***Undesirable Disturbance Study Team*** **(*UDST*)** concluded that:

> ***undesirable disturbance*** *is a perturbation of a marine* **ecosystem** *that appreciably degrades the* **health** *or threatens the* **sustainable human use** *of that ecosystem[,]*

whilst pointing out that a variety of anthropogenic and natural causes of ecosystem disturbance operated in UK salt waters. The latter were seen as comprising all UK continental shelf waters including the WFD's *coastal waters* and its *transitional waters* to an inner limit where the flora and fauna cease to have a substantial marine component.

Stage 2 of the study (Anon, 2004b) concerned development of a UK assessment methodology for ***undesirable disturbance*** in coastal and marine waters, and led to the ***checklist*** appended to this paper. The checklist summarizes the stage 2 methodology; the rest of the present paper aims to give an overview of related issues considered during the study.

Ecosystem health

According to Odum (1959)

> *any area of nature that includes living organisms and nonliving substances interacting to produce an exchange of materials between the living and nonliving parts is an ecological system or* ***ecosystem****.*

Since its purely factual definition in like terms by Tansley in 1935, the word ***ecosystem*** has acquired a halo of associated ideas, including those of the *balance of nature* and of *ecosystem health*. According to Costanza *et al. (*1992), a healthy ecosystem, like a healthy human body, is a system that functions well and is able to resist or recover from disturbance. However, the concept is more than a metaphor, because ***ecosystem health*** has quantifiable components which can be understood in terms of presently or potentially rigorous ecological theory. These components (Mageau *et al*, 1995) are its ***vigour*** and ***organization***, its ***resistance*** to disturbance, and its ability, called ***resilience***, to recover from disturbance. As seen by the UDST, the ***vigour*** of an ecosystem is related to the biologically-mediated fluxes of energy and materials through the ecosystem, and to the ability of the biological community to replace disturbed parts through population growth or the production and settlement of larvae. An ecosystem's ***organization*** (also called its ***structure***) involves its biological community's physical structure, food web structure, and biodiversity. The community's activities can structure the environment (for examples, through increasing sediment cohesion or building reefs), and ***resilience*** can also depend on features of the environment as well as those of the biological community.

These ideas are illustrated in Figure 1. Part (a) deals with ***vigour***, and suggests how enrichment of an *oligotrophic* ecosystem can at first improve its *trophic* (or nutritional) status to a condition of ***optimal*** vigour (which was the original meaning of *eutrophic*) and then take it to a ***dystrophic*** state. Part (b) deals with ***organization*** (or ***structure***), and suggests that an ecosystem impacted by anthropogenic factors may, because of its ***resistance*** to disturbance, initially show little response to increasing pressure. Pushed beyond a certain point, however, change becomes rapid, and may culminate in a radically altered state from which recovery is slow. An example would be the occurrence of extensive deep water anoxia, resulting in the widespread elimination of the macrobenthos. A key operational need is to detect a ***trend*** towards such a widespread ***undesirable disturbance*** before the ecosystem has reached the limit of its **resistance**.

The use of the concept of ecosystem health for defining undesirable disturbance requires the spatial extent of an ecosystem to be defined. For present purposes the system that is identified should have some hydrographical unity – so as to minimize the variability resulting from combining ecohydrodynamically different waters – but should not be so small that its state is overwhelmingly determined by outside events. Examples of suitably-sized ecosystems might be Belfast Lough, the Firth of Clyde, or the stratified region in the western Irish Sea. Given an ecosystem approach to undesirable disturbance, ***small-scale disturbances*** are not considered a cause for concern (they can be dealt with by *Allowable Zone of Effect* procedures) unless they impact on a *conservation feature*, in which case appropriate legislation applies irrespective of whether the disturbance has undesirable consequences for ecosystem health. Ecologists customarily distinguish episodic ***pulse*** from sustained ***press*** disturbances. Local, ***pulse***, ***disturbances*** are considered to be of little concern; a ***widespread pulse disturbance*** would be of concern if it brought an ecosystem to a ***crisis*** as a result of weak ***resistance***. ***Extensive press disturbances*** give the most concern as they can lead to a ***crisis*** from which the outcome may be a large change in ***biome*** or ***ecological quality status***. Such outcomes will be ***undesirable disturbances***, and movement towards the crisis would itself be a cause for concern. Crisis is here used by analogy with the point in an illness after which the patient either recovers or irreversibly changes state (and status), and is shown in Fig. 1(b) by the point at which the graph of structure against pressure begins to descend steeply.

Natural disturbance, and natural variability, are features of all ecosystems, and indeed, in *intermediate disturbance theory* (Connell & Sousa, 1983) are seen as an important generator of biodiversity. Anthropogenic disturbance must be thus be assessed against natural variability and disturbance. In relation to ecosystem ***vigour***, the UDST saw one of the key requirements for health as being the maintenance of good ***coupling*** between primary producers and their consumers. Should this coupling break down extensively in time or space, the result would be an excess of organic matter which could impact adversely on deep water and benthic communities. It is this breakdown which is the cause of ***dystrophy***, and not high production as such.

The balance between producers and consumers is to be seen as part of the community's ***structure***. Also part of the structure are some aspects of biodiversity. The UDST concluded that what was crucial for health was not a certain total number of species but, rather, the maintenance of a proper balance amongst ***guilds*** of benthic animals or, more generally, amongst ***lifeforms*** of organisms. An example benthic guild is that of large burrowing animals. These play a vital role in the benthic community and for the geochemical state of the sediment by flushing pore waters more rapidly than diffusion can. A number of species can do the work; characteristically, not all are found at any given location or in any given sample.

Mapping to OSPAR and WFD criteria

EC and OSPAR definitions of eutrophication include *undesirable disturbance to the balance of organisms*. Stressing the need to maintain the structural component of ***ecosystem health*** is a restatement of the need to avoid such an undesirable disturbance**.** Of the 5 OSPAR ***Ecological Quality Objectives*** (***EcoQO***s) considered for application to UK waters (Painting et al., 2004), winter nutrient concentrations are used here only as indicators of pressure. Objectives referring to chlorophyll, phytoplankton indicator species, dissolved oxygen and zoobenthos are considered below. It is proposed that WFD *poor* status can be equated with an undesirable disturbance to ecosystem health. Good health corresponds either to *high* status (when no disturbance can be detected against a background of natural variability) or *good* status (when disturbance is just detectable). WFD *moderate* status does <u>not</u> correspond to an undesirable disturbance or to poor ecosystem health; indeed, system vigour might be *optimal* as defined above. However, an ecosystem in this state, albeit only moderately altered from reference conditions, could be on the brink of rapid change if its ***resistance*** is about to be overwhelmed. Thus a trend from *good* to *fair* status may give cause for concern by suggesting that an ecosystem is tending towards (although has not yet reached) dystrophy, poor health and undesirable disturbance.

Ecohydrodynamics

Ecohydrodynamics takes account of biogeographical variation in the species available to populate an ecosystem as well as of the physical structure and dynamics of a water body (and the effect of these physical and biological factors on the sea-bed). Biogeography is exemplified by the decreasing abundance of copepods of the genus *Calanus* with distance from the shelf break, and physical dynamics by the difference between stratified and mixed water. Ecohydrodynamics controls a water body's response to nutrient enrichment and thus the likelihood and nature of disturbance. A comprehensive knowledge of ecohydrodynamic types in UK waters is needed to supply reference conditions against which to assess disturbance. A simplified typology is used in the ***checklist***, described below, to specify which parts of the proposed methodology be used in a given water body. This typology distinguishes:

- shallow clear waters, in which the euphotic zone includes the seabed, and where ***phytobenthos*** are characteristically important;
- optically deep ***mixed waters*** where phytoplankters are unlikely to be stimulated by nutrient enrichment;

- ***offshore stratified waters***[1], which naturally have a nutrient-depleted surface layer during summer and so where extra nutrients can stimulate phytoplankton growth and production, and bring about deep-water oxygen depletion;
- ***Regions of Freshwater Influence (ROFIs***), which are highly variable inshore waters that are characteristically energetic because of tidal and wind-wave stirring, turbid with suspended sediment, and with a moderate or high freshwater content which may bring about intermittent stratification;
- ***Regions of Restricted Exchange (RREs),*** which are inshore, semi-enclosed waters whose dynamics and eutrophication risk depends on the rate of water exchange with the sea; the category includes ***fjords*** (some of which have ***basin deep water***[2]), rias, other types of estuary, and coastal embayments and straits.

Freshwater, in addition to potentiating stratification and circulation, is also the main bringer of anthropogenic nutrients into many UK waters. However, diffuse inputs from the atmosphere, and point sources such as fishfarms, may also need to be considered. Furthermore, UK offshore waters influenced by Atlantic inflow would, under natural conditions, have higher nutrients than inshore waters. Finally, submarine ***optical*** conditions are critical in some cases, in determining whether phytobenthos or phytoplankton may grow, and are themselves altered by phytoplankton growth.

Measurement issues

Detection of disturbance requires measurement, followed by categorization, of ecosystem properties. What, in general, should be measured? Some definitions will be useful. A ***state variable*** is one of a set of continuous variables that together uniquely define the state of a system such as an ecosystem. ***Status*** refers to a division of all possible states into a set of categories which can be arranged in a ranked sequence and associated with judgments about desirable and undesirable ecosystem conditions. An ***indicator*** is any continuous variable that points to some aspect of the state or health of an ecosystem. Such variables may be scalar or vector, state variables or derived variables including statistics, or time derivatives sometimes identified as rates or fluxes. They can include the abundance or health of organisms belonging to ***indicator species***. Finally, ***index*** (plural *indices*) is used to mean a non-dimensional variable formed from a ratio, or ratios, of indicator(s) to reference value(s).

Figure 2 illustrates the idea of ecosystem state. The 2-dimensional diagram of Fig. 2(a) is drawn in a phase or state variable space defined by only two variables, y_1 and y_2, and is intended to represent a multidimensional space which cannot be drawn. However, the plotted variables could also be understood as statistics, summarizing more complex variation. The stippled doughnut is the region that includes all those states of the ecosystem that are normal for the type-specific conditions, taking account of seasonal and interannual, variation and spatial patchiness. The system is deemed to be healthy while its state remains within, or is capable of returning rapidly to, the doughnut. Bad health consists of sustained movement away from the doughnut, and this is shown as constituting an ***undesirable disturbance***. The

[1] The category includes waters that are thermally stratified from late spring through early autumn, those that are thermohalinically stratified, perhaps for a greater part of the year, and frontal regions of intermediate seasonal stratification. Some typologies might distinguish these different stratification regimes.

[2] The upper waters of most fjords exchange regularly with the sea as a result of wind-driven, tide-driven, or density-driven, circulation, the density driven circulationr esulting mainly from differences in freshwater content. ***Basin deep water,*** below the depth of a fjord's entrance sill, can be isolated from the regular circulation and flushed at intervals that may be irregular and sufficiently long for the water to become depleted of oxygen.

movement could lead to a new stable state or region or attraction - i.e. another doughnut - might be healthy in absolute terms, but nevertheless ***undesirable*** because of the change of state and perhaps ***biome***, or it could clearly be less healthy, as in the case of a benthos smothered by a blanket of particulate organic matter.

Fig. 2(b), taken from the time series data collected at the PML L4 station in the English Channel, instances such a state-space plot, the two state variables being diatom abundance and copepod abundance (and these are of course bulk statistics, derived by aggregating abundances of species). Weekly values over a 2 year period are plotted against each other. The diagram brings out the extent of the week-to-week and interannual variability that must be taken into account, in addition to the seasonal changes, in making an adequate description of system state.

In the present context it is necessary to distinguish disturbance caused by nutrient enrichment from that due to other causes. In the case of existing undesirable disturbance, this can be done by seeking theoretical or empirical links to nutrient enrichment; and, in the case of trends in indicators, by looking for correlation with trends in nutrient loading. In both cases it is important to have simultaneous data from reference sites, which provide a control on changes at the disturbed sites. The use of validated ***numerical models*** may allow the impact of added nutrients (as opposed to other pressures) to be quantified.

Pelagos

Nutrient enrichment of the ***pelagic*** part of a marine ecosystem can impact on phytoplankton, pelagic microheterotrophs (bacteria and protozoa) and metazoan zooplankton. Criteria for assessing such impact include:

- existing UK quality standards, such as the *Comprehensive Studies Task Team* (*CSTT*) eutrophication threshold of 10 mg chl m^{-3} in summer;
- the OSPAR *ecological quality elements*: phytoplankton chlorophyll; phytoplankton indicator species for eutrophication; dissolved oxygen;
- the WFD *biological quality elements* (contributing to *ecological quality status*) of phytoplankton, composition and abundance of taxa, biomass, and frequency and intensity of blooms;
- ***ecosystem health*** indicators relating especially to ***structure*** and ***vigour***;
- statistics relating to sustainability of human use, such as the frequency of ***Harmful Algal Blooms*** *(HABs)*.

Four sets of indicators seem useful for detecting undesirable disturbance of the pelagic part of marine ecosystems:

- bulk indicators of ecosystem state, especially water transparency and the concentrations of chlorophyll and of sub-pycnocline oxygen, which in turn may act as pressures on other ecosystem components;
- indicators of ecosystem ***structural health*** that involve identification and enumeration of microplankters (including phytoplankters) and zooplankters;
- flux measurements, indicative of ***vigour*** or ***dystrophy***, especially annual primary production, and deep-water oxygen consumption rate;
- frequency statistics, such as those for HABs.

The UDST proposed the following strategy for monitoring:

(1) identify waters which could be at risk from undesirable disturbance because of nutrient ***enrichment*** plus ***ecohydrodynamic*** conditions that allow nutrient-fuelled increases in production without effective ***coupling*** to consumers, or which favour accumulation of organic matter below a pycnocline;

(2) in waters where disturbance is possible, consider chlorophyll concentrations, the frequency of HABs, and in appropriate cases, transparency, and deep-water oxygen; if these breach an appropriate (type-specific) EcoQO or if they show an trend, year-on-year, that correlates with nutrient increases, then further study is required except in the case of small water bodies where it might be more cost-effective to assume undesirable disturbance;

(3) further study should involve estimation of annual primary production and the monitoring of plankton composition for comparison with a reference conditions.

Chlorophyll concentration has long been used as an indicator of phytoplankton biomass and photosynthetic potential, and can be measured both by standard water sampling methods and operational use of in situ fluorometry. Increased chlorophyll concentration decreases ***transparency*** and thus impacts on the phytobenthos in shallow waters.

There is no linear mapping from production to disturbance, and the level of production at which ecosystem ***vigour*** passes beyond an optimum to a ***dystrophic*** condition in which there is a danger of hypoxia or anoxia in deep water or sediment, depends on ecohydrodynamic conditions and the effectiveness of ***coupling*** between primary producers and their immediate consumers. In seasonally-stratified, or basin, deep waters, measurement of minimum oxygen concentration and rate of consumption are needed to assess this. Annual primary production should be measured in all large water bodies by an efficient methods combining measurement of photosynthetic parameters with routine measurements of chlorophyll and calculations of light penetration (Fig. 3). The possibility of ***dystrophy*** should be considered above a ***net microplankton production*** of 200 g C m^{-2} yr^{-1}. This is lower than Nixon's (1995) threshold of 300 g C m^{-2} yr^{-1} for ***eutrophic*** conditions, but is a precautionary value, and its surpassing points to a need for further study rather than diagnosing undesirable disturbance. It is likely that dystrophy will in fact only occur at much higher levels of production.

Infrequent HABs are not a cause for concern, even if they result in local nuisances, on in local mortalities of fish or benthos. They are often natural. However, a trend of increase in the frequency of HABs, compared with a reference condition, is a cause for concern. There is a need for an agreed definition and co-ordinated record of HABs. This record should initially be restricted to large-biomass events (including Red Tides) which either cause a documented nuisance or kills of wild farmed animals, or contain species with the potential to do this. For the present, incidents involving ***Shellfish-Vectored Toxins*** (***SVT***s) should not be counted, but studies of the relationship between these and nutrient levels are desirable.
Remote sensing of phytoplankton and primary production is presently of limited operational value in the optical class 2 conditions of most UK coastal waters, where the main optically active constituents are suspended particulates and yellow substance. However, there are waters where remote sensing can be used to record the occurrence and extent of HABs, given a minimum sea-truth, and such regions should be identified as part of ecohydrodynamic typing. Example images can be obtained from the Plymouth Marine Laboratory Remote Sensing Group (www.npm.ac.uk/rsdas/) and include those at http://www.npm.ac.uk/rsdas/projects/ shetland_bloom/.

Monitoring of the structure of the plankton requires high frequency observation of each component, including the main taxonomic and functional groups of phytoplankton, pelagic protozoa and metazoan zooplankton. The time series maintained by the Plymouth Marine Laboratory at the L4 station in the English Channel (see: http://www.pml.ac.uk/L4) exemplify the resolution needed. Continuous Plankton Recorder Survey data are less useful because the recorders select for certain organisms and are not deployed close to shore. However, they are vital for documenting long-term, wide-area, changes, such as those due to climate change and fisheries, which impact on reference conditions for eutrophication. The study team concluded that that there are no individual species of phytoplankton, or indeed zooplankton, which are useful indicators of eutrophication. Instead there is a need for holistic analysis of plankton ***state.*** Data should be plotted, perhaps in a statistical reduction of multidimensional state variable space, for comparison with ***envelopes*** obtained under reference conditions. Sustained deviation from the envelope diagnoses ***undesirable disturbance.*** A ***phytoplankton trophic index (PTI)***, and a ***plankton community index (PCI)***, should be developed to simplify this task. Studies should be carried out with candidate PCIs to find one that is a good indicator of the efficiency of producer-consumer ***coupling***.

Phytoplankton are the crux of the matter in diagnosing eutrophication, not only because they provide the initial response to nutrient enrichment, but also because it is now clear that they encompass a huge range of taxonomic and functional diversity which cannot be ignored in assessing the health of marine ecosystems. Monitoring is initially likely to emphasise the role of diatoms and armoured dinoflagellates, but must ultimately include the smaller algae and the protozoa that help control them. Human microscopical examination of plankton samples must for the present remain the core method of analysis. Flow cytometry may be worth considering for smaller phytoplankters. Two other methods, presently non-operational may repay further study. Both relate to the photosynthetic accessory pigments that differ amongst the major taxa of phytoplankton. The pigments can be chemically separated using HPLC, or distinguished by their different spectral light absorptions.

Automated devices, including moored ***Smartbuoys***, and ***Ferryboxes*** on ships making regular crossings, can measure physical and optical variables and the concentrations of chlorophyll and nutrients. They can thus provide the high frequency data needed especially in regions of high physical variability (such as ROFIs) and could allow estimation of pelagic ecosystem ***resistance*** to nutrient pressure by measuring the yield of chlorophyll from nutrient. Finally, they can take and preserve samples for phytoplankton.

Benthos

The benthic environment and the macrozoobenthos respond to disturbance in well-characterized ways. However, few of these responses are unique to the pressure of nutrient enrichment or offer sensitive indicators of undesirable disturbance in the context of eutrophication. In shallow waters, natural physical disturbance is often the dominant effect. and the deep water benthos is often impacted by fisheries gear. So far as the consequences of nutrient enrichment are concerned, the main effects are likely to be:

- subtle changes of benthic community structure resulting from increased food supply;
- intense local pulse disturbances resulting from sinking Red Tides;
- chronic changes in community structure as deep water oxygen content falls and/or the anoxic region of the sediment extends towards the surface;

- catastrophic widespread destruction of deep water benthos associated with extreme hypoxia and anoxia.

The latter would of course be an *undesirable disturbance*, and has occurred in the deep water of the Baltic Sea as a result of increased nutrient loading of water which experiences long intervals of stagnation (Fonselius & Valderrama, 2003; Laine et al., 1997). Excepting a few sea-lochs, UK waters are not at risk of this. Monitoring against undesirable disturbance must thus be able to detect relatively subtle changes in community structure, or changes in environmental conditions that drive these. Such conditions include sediment organic carbon content and deep-water and sediment oxygen concentrations. Indicators for the state of benthic communities include: **indicator species** as such; indicators of groups of species known to be disturbance- sensitive or insensitive; and holistic measures of community ***structure*** including ***diversity indices*** and ***trophic indices***. The last are those derived from data on the relative abundance of different feeding types or ***guilds*,** and are perhaps better called ***Benthic Community Indices (BCIs)***. All such measures of structure are subject to the great natural variability of the benthos, and so need many replicate samples to provide a precise value. The UK National Marine Monitoring Programme is currently reviewing some of these indexes.

New techniques involving imaging are likely to prove useful. Cameras on towed benthic sleds can serve to estimate, for example, the population density of burrows in muddy sediments and thus the abundance of the burrowing animals. *Sediment Profile Imagery (SPI)* can be used to measure the depth of the ***Redox Potential Discontinuity*** (***RPD)*** which is a good indicator of habitat quality in soft sediments (e.g. Nilsson & Rosenberg, 1997).

Taking account of these considerations, the proposed monitoring strategy is to evaluate:

- **minimum concentrations**, and **rates of consumption**, of **oxygen** in seasonal and basin deep water, together with **RPD depth** measured by **SPI**, as indicators of ***vigour*** in the sense of relating to conditions that can lead to ***dystrophy***;
- values of one or more relevant ***BCI*s**, such as the ITI or AMBI, together with estimates of the population of an **indicator species** such as *Nephrops norvegicus* (an important bio-engineer in deep mud sediments and sensitive to low oxygen concentrations), as indicators of the ***structure*** component of ecosystem health.

In respect of deep water oxygen, the UDST suggested that concentrations should remain above 4 mg L^{-1}. It seems that the RPD should be deeper than 2 cm to allow the existence of a *normal* macrobenthic community, but this needs further investigation, and the value may depend on ecohydrodynamic type. Similarly, ranges of values of the ITI and AMBI have been proposed for *normal* conditions or *good* or *high* quality status (Codling & Ashkey, 1992; Borja et al., 2004), but such ranges need further investigation in relation to the specific types of environmental pressure and disturbance resulting from nutrient enrichment. Thus it is recommended that monitoring be used to compare indicator values with an appropriate reference condition and examine trends over time. Differences and trends should be further examined for correlation with nutrient levels.

Phytobenthos

Some of the tools being developed for assessment of WFD biological quality elements by the *Marine Plants Task Team* (*MPTT*) may provide indicators of undesirable disturbance due specifically to nutrient enrichment. So far as the phytobenthos is concerned, only two undesirable consequences of eutrophication occur on UK coasts. They are the mass blooming of macroalgae on tidal flats, and seagrass decline. These problems occur mainly on sedimentary shores in localized areas.

The concept of *macroalgal indicator species* is not useful in terms of estimating ecological quality. All the nuisance or opportunist green and brown seaweeds are important members of their communities under good conditions. It is the loss of other species rather than the gain of these indicators that is the problem. A better method is to use bulk features of cover by the opportunists, including:

- Area covered;
- Biomass density;
- Evidence of adverse effects due to the weed cover.

One criterion for eutrophication proposed by the MPTT is that it has occurred when more than 25% of the available intertidal area is covered with green macroalgae of greater than 25% cover. The intertidal areas included in this assessment are soft-sediment only, as high levels of macroalgae can naturally occur on rocky shorelines. A second criterion is that of (annual maximum) biomass exceeding 1 kg m^{-2}. Adverse effects can include:

- Invertebrate fauna reduced, in general, or numbers of commercially exploited shellfish, such as cockles, reduced in particular;
- Wading bird feeding distribution modified;
- Floating rafts of weed affecting boating activity, or deposited weed smothering other salt marsh vegetation, or anoxia in surface sediment layer (e.g. top 2 cm), or public complaints about odour.

Four tools have been proposed by the MPTT for the assessment of sea-grass beds. They are:

- ***areal cover*** and ***density*** (as shoot density or % cover) as non-destructive indicators of abundance;
- ***progress of the Wasting Disease*** (in subtidal seagrass species only) and ***epiphyte cover***.

None of these indicators are specific to eutrophication, and so it is necessary that trends in their values by examined for correlation with trends in nutrients. Because of the important conservation status of seagrasses, any correlated trend of decreasing abundance or health should be deemed an ***undesirable disturbance***.

Checklist

The parts of the methodology developed by the UDST for the monitoring and diagnosis of ***undesirable disturbance*** due to anthropogenic nutrients have been synthesized in a checklist, which is appended to this document. The main steps in using the methodology are:

- assess ecohydrodynamic type (and thus, in principle, the reference conditions);
- assess nutrient loading, and hence identify water bodies/ecosystems where there is potential for undesirable disturbance in the context of eutrophication;
- use bulk and frequency indicators, and in some cases tools such as that of the CSTT eutrophication model, in comparison with reference conditions, to make a provisional diagnosis of nutrient-induced disturbance;

- use correlation between (adverse) trends in these indicators and in nutrients to support the provisional diagnosis or to identify water bodies or shores that should be subject to continued detailed monitoring;
- use primary production (a part of ***vigour***), and indicators of planktonic and benthic community ***structure***, to assess departures from good ***ecosystem health***; in some cases the state of populations of indicator species will form part of the health assessment.

In addition to analyses for trends and correlations, most indicators are also to be assessed against an appropriate EcoQO. Two types of EcoQO are considered here:

- the value of an indicator shall not exceed (or not fall below) a certain standard value, which may be absolute or may relate to reference conditions;
- no more than 5% of values of an indicator shall fall outside of an ***envelope*** of variability defined for the appropriate reference condition; the envelope may be either that of property plotted against time, or that in phase space (Y_1-Y_2 etc plots).

Envelope plots are particularly appropriate in the case of the plankton, because of the very large amount of natural short-term, seasonal and inter-annual variability shown by both bulk measures of plankton components and the abundance of individual species in UK salt waters. An example property-time envelope plot is given in Fig. 4.

The checklist include several possible diagnoses:

- ***insufficient data***;
- a ***trend*** towards undesirable disturbance related to nutrient enrichment;
- ***undesirable disturbance*** due to nutrient enrichment.

Given that water bodies and ecosystems will be assessed only if they have been identified as at risk because of nutrient enrichment under sensitive ecohydrodynamic conditions, the remedies for ***insufficient data*** are simple. Either data collection must be started urgently, or else the *precautionary principle* must be invoked and action to reduce nutrient inputs taken as if ***undesirable disturbance*** had been diagnosed. An identified adverse ***trend*** implies that a water body or shore should be the subject of continued frequent monitoring. It does not mean that action <u>must</u> be taken to reduce nutrient inputs because increasing primary production might on balance be more beneficial than harmful to ecosystem health. The diagnosis of ***undesirable disturbance*** may be made at several stages in the analysis. The ideal diagnosis will take account of all indicators, including those relating to ecosystem structure and vigour, and this is what the study team recommends for large water bodies - not only because of the cost implications of the diagnosis but also because of the unknown long-term risks of misunderstanding the state of a large part of our salt waters. However, a provisional diagnosis from bulk or frequency indicators may be accepted as final in the case of smaller water bodies or shores, where the cost of measurement of structure and vigour may outweigh the cost of nutrient reduction.

Recommendations

Finally, the UDST suggested that there should be a 4-year study of the Irish Sea, including adjacent waters such as the Firth of Clyde and the sea-loughs of Northern Ireland, with the aim of testing and using the methodology developed in this work on ***Undesirable Disturbance***, building on existing and planned programmes. Having tested and refined the methodology and checklist in the (broader) Irish Sea, it should be applied to other UK waters, commencing with an identification of ecohydrodynamic regions and characterization of the plankton communities therein under reference conditions.

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Figure legends

1. Ecosystem *health* and undesirable disturbance. The primary components of *health* are good ***structure*** and optimum ***vigour***. These lie behind the ecosystem's ***resistance*** to pressure and ***resilience*** in recovering from disturbance. (a) relates health to vigour as this increases with nutrient enrichment; (b) shows the typically non-linear response of structure to pressure.

2. Ecosystem state. (a) is a diagram relating state and disturbance; (b) plots data from the Plymouth Marine Laboratory L4 station, available at http://www.pml.ac.uk/L4.

3. The 'PIRX' method of estimating primary production. PIRX is an acronym combining Photosynthesis as a function of Irradiance, taking account of Respiration, and multiplying by chlorophyll concentration (X) to get production.

4. **Envelopes of variation for DAIN** (called here, *total inorganic nitrogen (TIN))* **and chlorophyll at the Fairway station in Liverpool Bay, 1990-1999** (EA data), compared with envelopes for supposedly pristine Loch Creran during the 1970s (re-analysed by Tett & Edwards, 2003, who give primary sources).

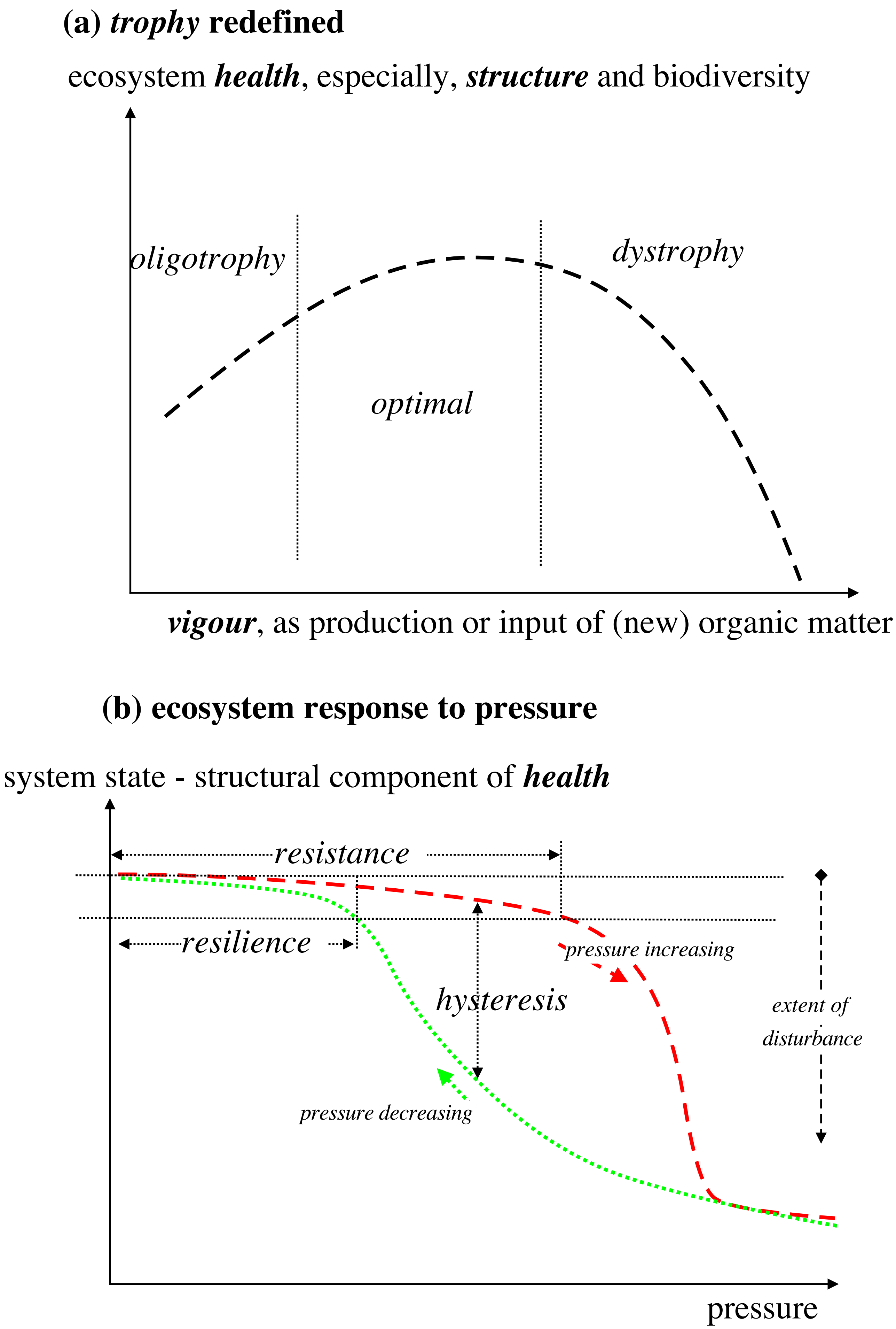
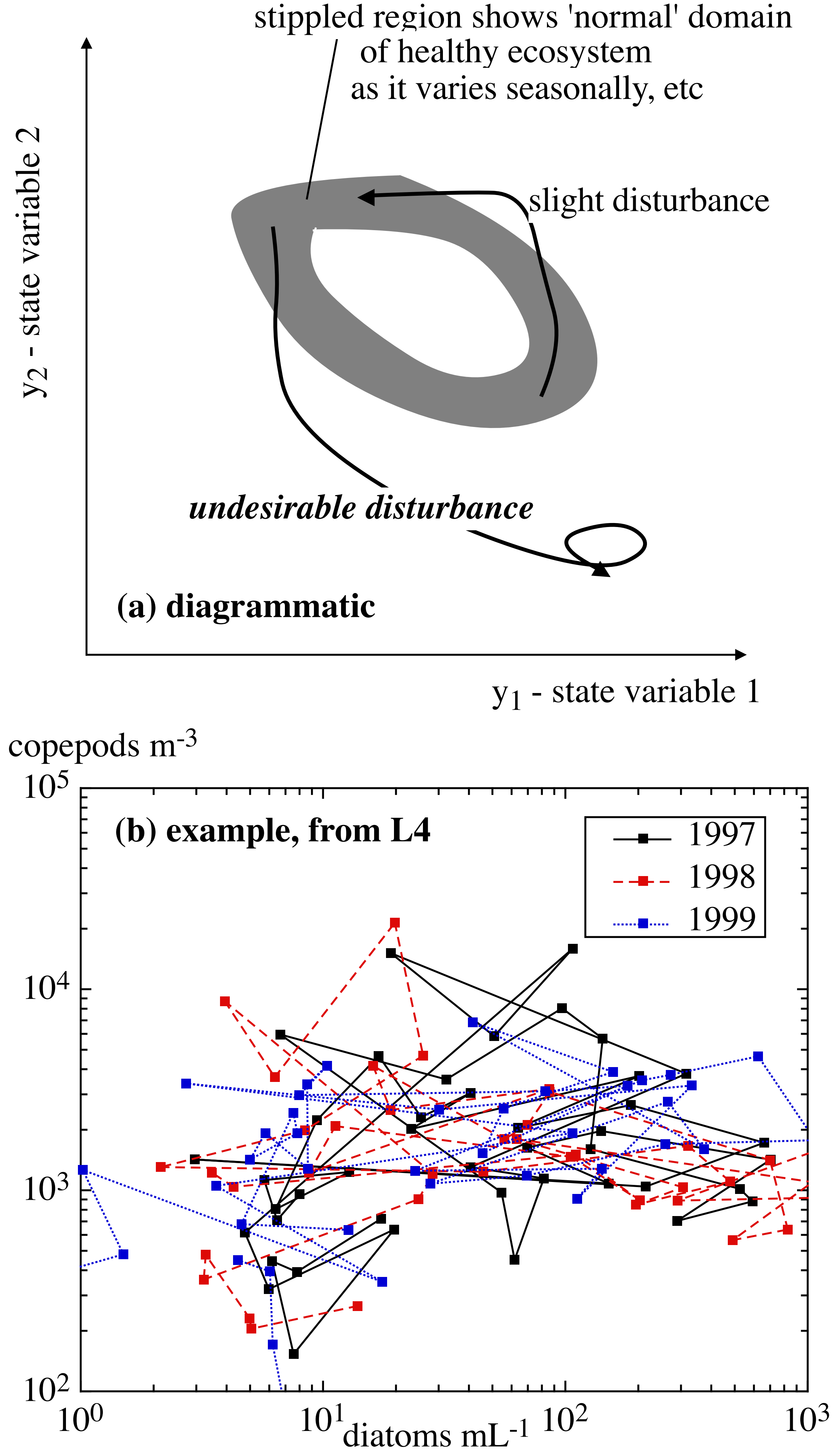


Figure 1. Ecosystem health

Fig. 2. Ecosystem state



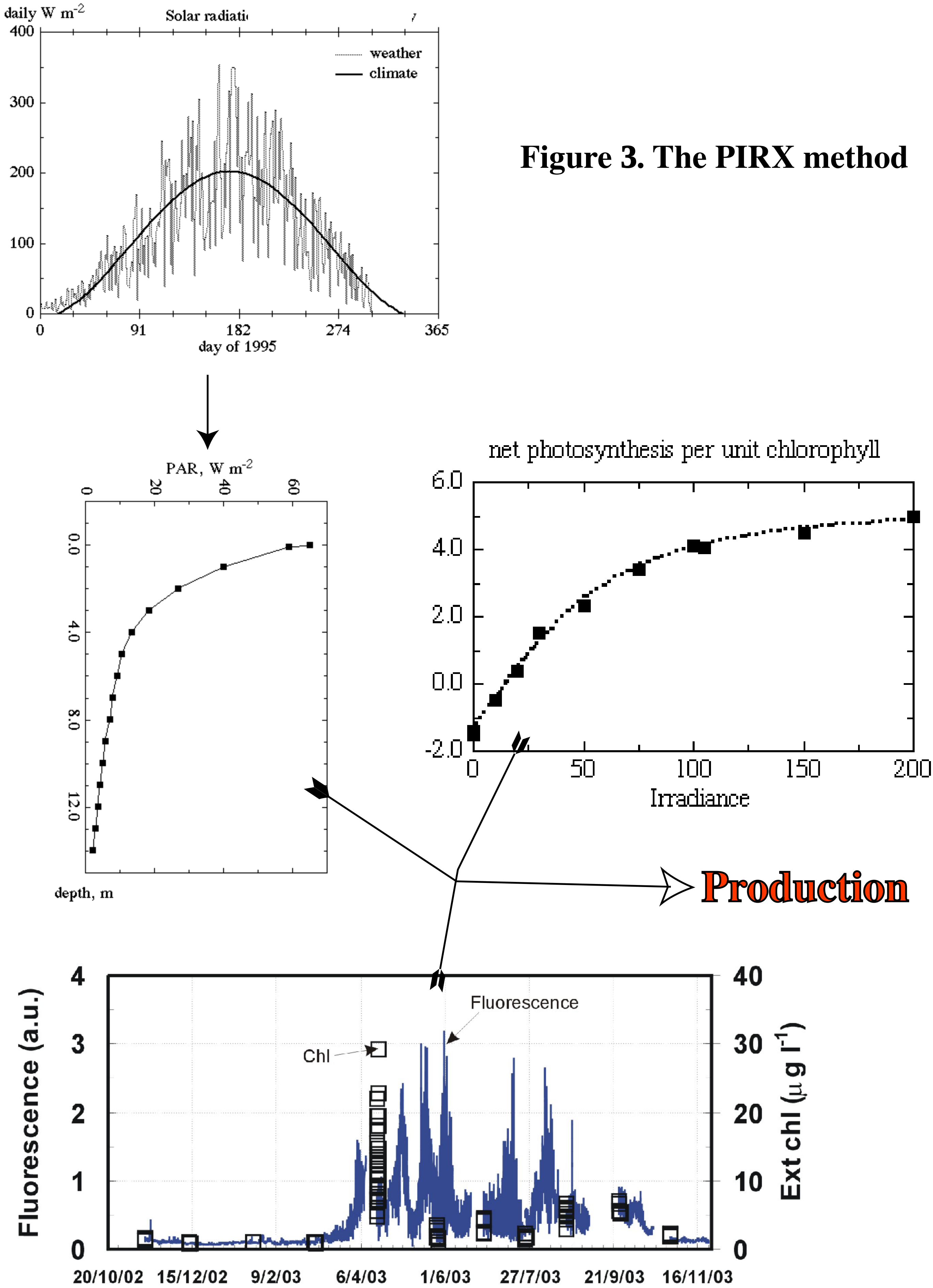


Figure 3. The PIRX method

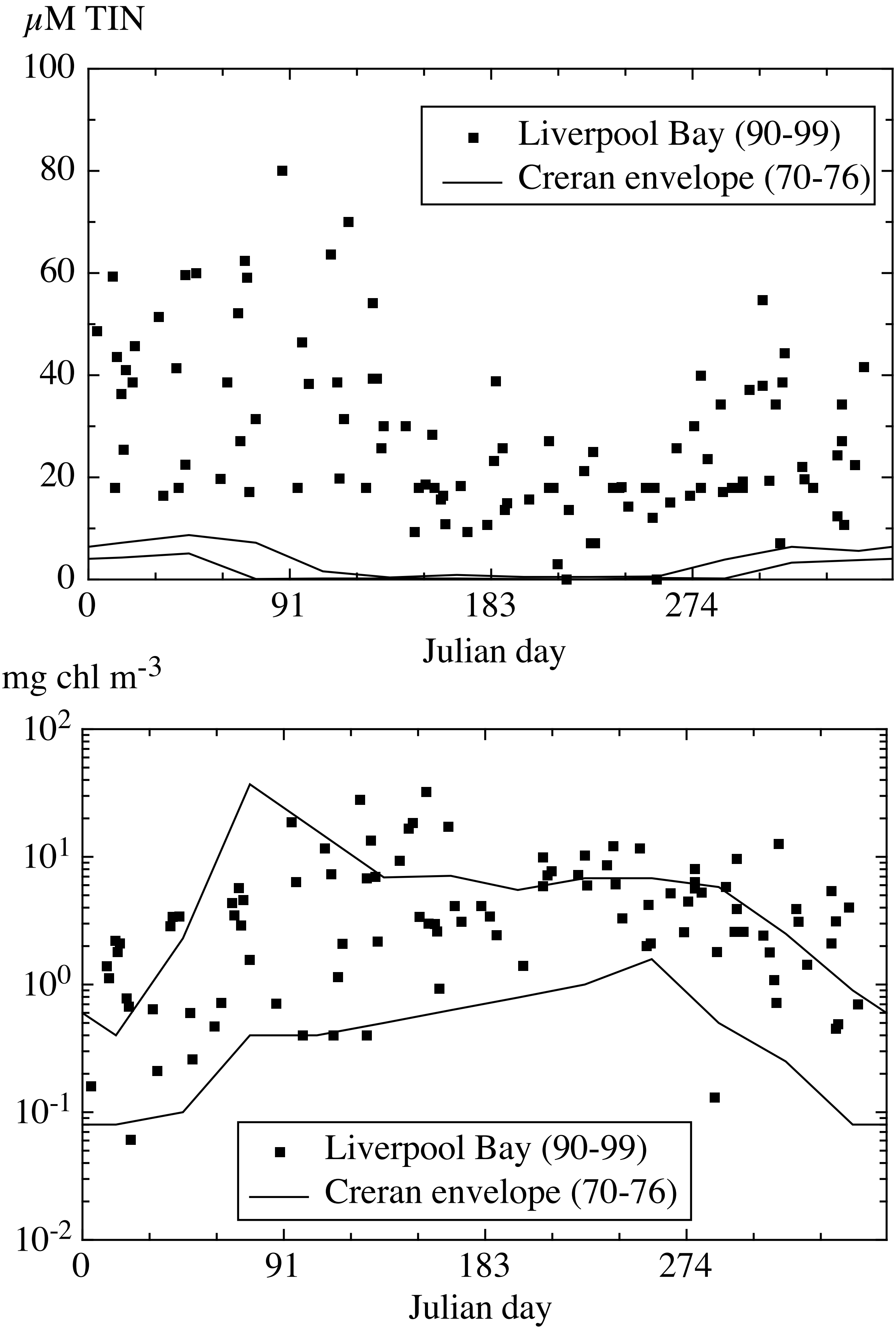


Fig. 4. Liverpool Bay - Fairway compared with Loch Creran