Monitoring for Adaptive Management of Aquaculture

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Abstract

Adaptive management is the key to the application of the Ecosystem Approach to the effects of aquaculture on the natural environment. Monitoring is part of adaptive management. Designing a monitoring strategy starts by establishing Environmental (or Ecological) Quality Objectives (EQO) relating to conservation of biodiversity and protection of ecosystem structure and function; this is illustrated with the Qualitative Descriptors of the MSFD and the Ecological Quality Elements of the WFD. The next step is to identify Pressures arising from aquaculture and to determine the spatial and temporal Scales on which they will bring about significant changes in the State of aquatic ecosystems, such as to give rise to a risk of failing the EQO. The most efficient adaptive management requires the preparation of Pressure-State relationships which, with suitable Environmental/Ecological Quality Standards (EQS), and taking account of uncertainties, will allow managers or regulators to plan ahead for the development of farms or industries.

Contents

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1 Introduction

The Ecosystem Approach (EA) is best implemented through adaptive management. This essay describes a strategy for monitoring as part of adaptive management of the effects of aquaculture on the natural environment. As listed in the previous essay (Tett, 2017) the relevant principles of the EA are EA05 and EA06 (maintain ecosystem structure and functioning) and EA10 (conservation and use of biodiversity). In addition there are matters relating to spatial and temporal scales (EA07, 08) and the dynamic nature and variability of (aquatic) ecosystems (EA06, 09). The essay will, also, introduce two European environmental Directives, the Marine Strategy Framework Directive (MSFD) and the Water Framework Directive (WFD) in order to provide consistent sets of quality objectives for aquatic ecosystems. However, whereas managers of marine regions (MSFD) or water-bodies (WFD) are required to monitor many aspects of ecosystem health, monitoring for management of individual aquacultural enterprises (hereafter 'farms') needs to be cost-effective. It should, thus, focus on the environmental effects likely to be caused by particular technologies.

2 Principles of Adaptive Management

I start by defining the terms *Pressure* and *State*, part of the DPSIR (Luiten, 1999) or DPSWR (Cooper, 2013) frameworks for describing interactions between humans and nature.

Pressure: "a manifestation of human activities that directly acts on the environment" (Cooper, 2013, summarizing earlier literature); I see it as an anthropogenic change in the 'boundary conditions' of an ecosystem (Appendix A);

State: the condition (at a defined moment or over a defined period) of the ecosystem or a part of an ecosystem such as a species population, a habitat, or an element of structure and vigour.

Non-adaptive management of the environmental effects of aquaculture would, as discussed in the previous essay, mean the stringent application of the precautionary principle to prevent damage to aquatic ecosystems, given that insufficient is known about effects of Pressures on ecosystem State. Adaptive management allows aquacultural industries and farms to develop, subject to adequate monitoring of their effects.

As a minimum, adaptive management of the natural environment of aquaculture needs:

- a goal to manage to
- identification or construction of an appropriate indicator S of State
- monitoring of State by use of S
- management action if a threshold value of S is crossed.

The management goal is variously called an *Environmental* or *Ecological* [Quality] *Objective*: it defines the desired State of the ecosystem component of interest. I will use the acronym EQO.

The next idea is that of an *Environmental* or *Ecological Quality Standard* (EQS), which I will use to refer to a defined level of a Pressure or State indicator that serves as a trigger for management action. This is more general than the WFD (article 2.35) definition that "'Environmental Quality Standard' means the concentration of a particular pollutant or group of pollutants in water, sediment or biota which should not be exceeded in order to protect human health and the environment."

Table 1: The issue of Eutrophication used to illustrate Adaptive Management terms

Eutrophication is defined as "the enrichment of water by nutrients especially compounds of nitrogen and phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms and the quality of the water concerned" (EU Urban Waste Water Treatment Directive, 1992).
An example *EQO*, from the MSFD's QD5, is that "eutrophication should be minimised".
An example *Pressure* indicator is the annual loading of a water-body with N and P from a fin-fish farm.
An example *State* indicator is the proportion in each year of water samples in which chlorophyll (a measure of phytoplankton biomass) exceeds X mg m^{-3}, with X being given an appropriate value for the water-body or ecosystem type, and samples being taken on at least 12 evenly spaced occasions during a year. (Loosely based on a UK indicator (Devlin et al., 2011).)
An example *EQS* is Y% of samples exceeding an appropriate X; action should be taken if this standard is exceeded.

To make things concrete, I will suppose that a fin-fish farm is being expanded in a coastal sea. Because the fish excrete nutrients (compounds of the elements nitrogen and phosphorus), there may be a risk of *eutrophication* (Table 1). Which is to be avoided – that is the EQO. Monitoring should include measurement of water-column chlorophyll, and an appropriate State indicator might be the annual percentage of samples in which chlorophyll exceeds a reference value. Figure 1 shows values of the indicator plotted against time. As the trigger value, the EQS, is approached, action should be taken to reduce Pressure.

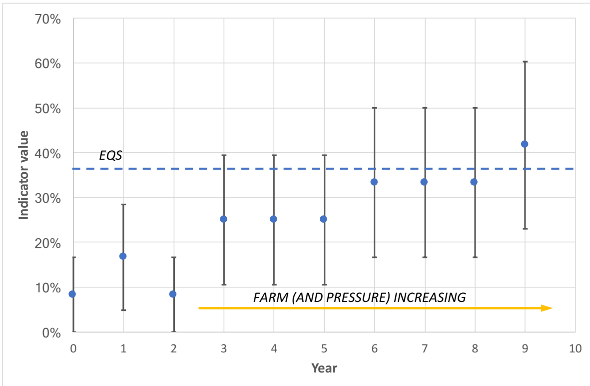

Figure 1: The use of a time-series a State indicator. S (that of Table 1) in adaptive management.

However, this is a rather inefficient way to manage. We can do better by

- identifying or constructing an appropriate indicator P of Pressure;
- developing a provisional $P \mapsto \Delta S$ relationship;
- anticipatory management of farm activity to control Pressure and prevent State failing to achieve the EQO.

- monitoring the system to obtain data for P and S indicators and to confirm or modify the provisional relationship;

The symbol $\mapsto$ refers to a 'mapping' from a Pressure Indicator to a State Indicator, meaning a mathematical relationship such as a linear or polynomial regression, allowing State to be predicted, with a certain level of confidence, from Pressure. Figure 2 shows a generic Pressure-State relationship; see also Appendix A.

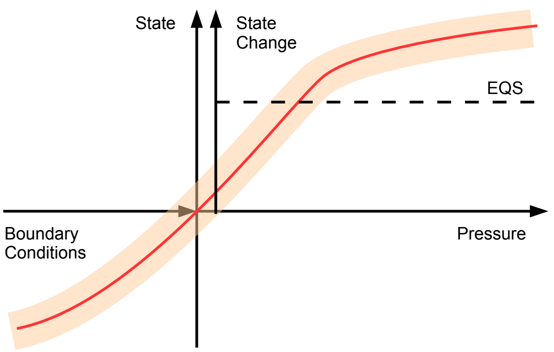

Figure 2: A Pressure-State relationship: the red line, with orange band showing uncertainty.

All that I have written in this section can be summed up with a definition of *Adaptive Management* (Ehler, 2014) as

> "the incorporation of a formal learning process into management actions." That is, "the integration of planning, implementation, monitoring and evaluation to provide a framework to systematically test assumptions, promote learning, and provide timely information for management decisions" .

3 Pressures

Figure 3 shows some of the effects of aquaculture in a water-body such as a small Scottish fjord, and Table 2 gives an indicative list of pressures associated with aquaculture in general. I will not consider these in detail, but it might be helpful for the reader to have in mind a few examples of Pressure indicators, such as:

- farm stock held or harvested, e.g. in tonnes of fish per year
- tonnes of fish feed supplied per month
- area occupied by shellfish or seaweed farm
- volume and content of waste water discharged from a tank or pond farm

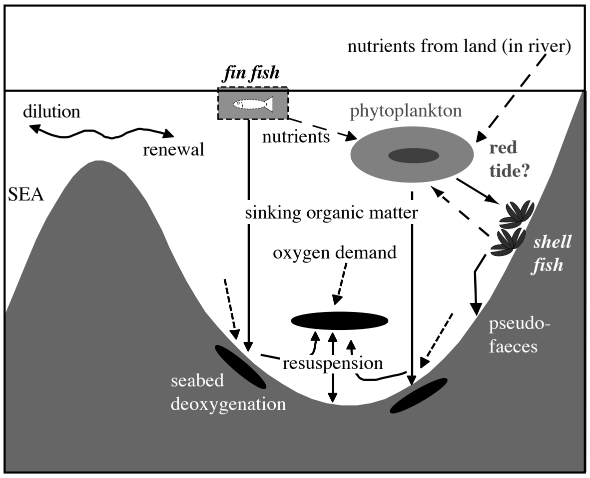

Figure 3: Effects of aquaculture in a small Scottish fjord, copied from fig 1.2 in Tett (2008)

Of course, these suggested quantities do not point directly at Pressures. A *Pressure*, as defined in section 2, is something that "directly acts on the environment". If we wanted to quantify what was acting directly, we would

Table 2: Some potential Pressures caused by Aquaculture, based in part on WFD annex VIII and MSFD annex III table 2.

Additions	Toxic substances (metals, organo-metal compounds and biocides) including those used in anti-fouling; Substances harmful in excess (organic wastes and plant nutrients): both categories included in WFD 'pollutants'. Fish medicines, including antibiotics.
Disturbances	Physical damage (by farm structures); Smothering (by organic waste from finfish, pseudofaeces from shellfish); Effects on temperature, salinity and water column structure and circulation; Underwater noise (from farm operation and predator deterrence).
Introductions	Alien species and new diseases (farmed non-local species, alien species and diseases introduced accidentally with farmed organisms or farm structures)
Removals	Nutrients (seaweed); Phytoplankton and Particulate Organic Matter (shellfish); Oxygen (all animals)

specify, for example, tonnes of Nitrogen released by a farm per month, kg chemotherapeutant entering the environment per farm treatment cycle, or tonnes of phytoplankton consumed by shellfish during a month. The indicators that I've listed above are one step removed from such quantifiers, but they are easier to measure and closer to what is directly manageable.[1] Thus it makes sense to use their values for the horizontal co-ordinates in P-S graphs exemplified by figure 2.

The next two sections are mainly concerned with State: they deal with goal setting as exemplified by EQO in two EU Directives.

[1] Models can be used to calculate the direct Pressures from the management indicators suggested here. Examples include DEPOMOD for benthic effects (Cromey et al., 2002; Brigolin et al., 2009) and LESV (Tett et al., 2011) for pelagic effects.

4 MSFD and GES

The first set of EQO is that in the **MSFD**, which is, in full, *Directive 2008/56/EC of The European Parliament and of The Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive).* The Directive's key aim is "to achieve or maintain good environmental status in the [EU] marine environment by the year 2020 at the latest". This aim is to be achieved with the use of "[a]daptive management on the basis of the ecosystem approach" (article 3.5).

Good Environmental Status, or GES, is defined (article 3.5) as

> the environmental 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

Table 3: Qualitative Descriptors 1 - 5 for determining Good Environmental Status, from Annex I of the MSFD, with example criteria from COM (2017).

	Title	Descriptor	Example criteria *and objectives*
1	Biodiversity	"Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions."	Population abundances of conserved species *are not "adversely affected due to anthropogenic pressures"* and ranges *are "in line with prevailing physiographic, geographic and climatic conditions."*; "condition of the [pelagic] habitat type ... *is not adversely affected due to anthropogenic pressures"*; "the extent of loss of the [benthic] habitat type, *resulting from anthropogenic pressures, does not exceed a specified proportion of the natural extent of the habitat type in the assessment area."*
2	Alien species	"Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems."	"The number of non-indigenous species which are newly introduced via human activity into the wild ... *is minimised and where possible reduced to zero."*
3	Fish stocks	"Populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock."	"The age and size distribution of individuals in populations ... *is indicative of a healthy population*".
4	Food webs	"All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity."	"The balance of total abundance between the trophic guilds *is not adversely affected due to anthropogenic pressures."*
5	Eutrophication	"Human-induced eutrophication is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters."	"Chlorophyll *a* in the water column" *does not "indicate adverse effects of nutrient enrichment"*; "the species composition and relative abundance or depth distribution of macrophyte communities ... *indicate no adverse effect due to nutrient enrichment including via a decrease in water transparency"* .

Table 4: Qualitative Descriptors 6 - 11 for determining Good Environmental Status

	Title	Descriptor	Example criteria *and objectives*
6	Sea-bed	"Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected."	Physical loss of, or disturbance to, the seabed or a specified benthic habitat type *shall not exceed a (sub-)regionally determined threshold.*
7	Hydrography	"Permanent alteration of hydrographical conditions does not adversely affect marine ecosystems."	"Spatial extent and distribution of permanent alteration of hyodrographical conditions ... associated in particular with physical loss of the natural seabed."
8	Pollutants	"Concentrations of contaminants are at levels not giving rise to pollution effects."	"Within coastal and territorial waters, the concentration of contaminants *do not exceed [specified] threshold values."* "The spatial extent and duration of significant pollution events *are minimised."*
9	Food safety	"Contaminants in fish and other seafood for human consumption do not exceed levels established by Community legislation or other relevant standards."	"The level of contaminants in edible tissues ... of seafood ... caught or harvested in the wild (excluding fin-fish from mariculture) *does not exceed [specified limits]"*; the proportion of species achieving the EQS shall be reported.
10	Litter	"Properties and quantities of marine litter do not cause harm to the coastal and marine environment."	"The composition, amount and spatial distribution of litter on the coastline, in the surface layer of the water column, and on the seabed, *are at levels that do not cause harm to the coastal and marine environment."* The same criteria and EQO applies to micro-litter (particles < 5μm) except that "in seabed sediment" replaces "on the seabed".
11	Noise	"Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment."	"The spatial distribution, temporal extent and levels of anthropogenic impulsive sound sources *do not exceed levels that adversely affect populations of marine animals."* The same criteria and EQO apply also to "anthropogenic continuous low-frequency sound".

is sustainable, thus safeguarding the potential for uses and activities by current and future generations, i.e.:

(a) the structure, functions and processes of the constituent marine ecosystems, together with the associated physiographic, geographic, geological and climatic factors, allow those ecosystems to function fully and to maintain their resilience to human-induced environmental change. Marine species and habitats are protected, human-induced decline of biodiversity is prevented and diverse biological components function in balance;

(b) hydro-morphological, physical and chemical properties of the ecosystems, including those properties which result from human activities in the area concerned, support the ecosystems as described above. Anthropogenic inputs of substances and energy, including noise, into the marine environment do not cause pollution effects;

GES is to to be evaluated on large scales, for example the 'Adriatic Sea' sub-region of the Mediterranean Sea, or the 'Greater North Sea' subregion of the North-East Atlantic Ocean. This evaluation is guided by the more detailed EQOs provided by a list of 11 **Qualitative descriptors** "for determining good environmental status", which are listed in Tables 3 and 4. It might be observed that the first part of this list deals largely with State, whereas the second part is more concerned with Pressures.

The QD were themselves elaborated in 2010 in a Decision of the EC Commission (COM, 2010), very recently superceded by COM (2017). Both these Decisions listed *criteria* that help to identify specific EQO and specific indicators, and in some cases to form EQS: selected examples of these criteria are included in Tables 3 and 4.

Whereas recent EC document (COM, 2016) concludes that only QD02 (concerning alien species) is likely to be substantially affected by aquaculture on the large scales considered by the MSFD, the tables of QD have an additional use in relation to smaller scales. They can guide us in deciding what should be monitored. For example, net-pen farms can affect benthos through settlement of organic matter and water-column through nutrient excretion. The criteria for QD05 and 06 point to Pressure and State variables that may need to be monitored in the vicinity of farms.

5 WFD and GEcoS

The second set of EQO come from the **Water Framework Directive (WFD)**. This is, in full, *Directive 2000/60/EC of The European Parliament and of The Council of 23 October 2000 establishing a framework for Community action in the field of water policy.* Amongst its aims is that of "protect[ing] and enhanc[ing] the status of aquatic ecosystems" in *Water Bodies*, which the WFD defines as "discrete and significant element[s] of surface water such as a lake, a reservoir, a stream, river or canal, part of a stream, river or canal, a transitional water or a stretch of coastal water." It is the effect of aquaculture within Water Bodies that is most likely to concern public authorities.

The WFD (article 2.18) equates (surface) *water status* with whichever is worse, the chemical status or the ecological status. Chemical status is defined in terms of a list of pollutants, which must all be present at concentrations below their EQS. This is in theory simple to monitor, but in practice managers may encounter complex issues of measurement and statistical analysis, as exemplified in a recent study of the environmental effects of the

Table 5: Quality Elements for the classification of Ecological Status in Coastal waters, from Annex V of the WFD. BQE = 'Biological Quality Element(s)'; TSC = 'type-specific conditions'

Category	Element	Criteria	Example definition for *Good* status
Biological	Composition, abundance and biomass of phytoplankton	*composition and abundance of phytoplanktonic taxa; phytoplankton biomass; bloom frequency & intensity*	slight changes in biomass compared to TSC. Such changes do not indicate any accelerated growth of algae resulting in undesirable disturbance to the balance of organisms present in the water body or to the quality of the water.
	Macroalgae and angiosperms	*presence of disturbance-sensitive macroalgal and angiosperm taxa; macroalgal cover and angiosperm abundance*	macroalgal cover and angiosperm abundance show slight signs of disturbance.
	Benthic invertebrate fauna	*diversity and abundance of invertebrate taxa; presence of disturbance-sensitive taxa*	diversity and abundance of invertebrate taxa is slightly outside the range associated with TSC.
Hydro-morphological	Tidal regime	*freshwater flow regime; direction and speed of dominant currents*	consistent with the achievement of the values specified for BQE.
	Morphological conditions	*depth variation, structure and substrate of the coastal bed; structure and condition of the intertidal zones*	consistent with the achievement of the values specified for BQE.
Physico-chemical	General conditions	*nutrient concentrations; temperature, oxygen balance and transparency*	Nutrient concentrations do not exceed the levels established so as to ensure the functioning of the ecosystem and the achievement of the values specified for BQE.
	Specific synthetic pollutants	*concentrations*	Concentrations not in excess of standards
	Specific non-synthetic pollutants	*concentrations*	Concentrations not in excess of standards

systemic anti-lice compounds used in salmon-farming (Edwards et al., 2016).

Ecological status (EcoS) is defined by WFD article 2.21 as

> "an expression of the quality of the structure and functioning of aquatic ecosystems associated with surface waters, classified in accordance with Annex V".

EcoS has five possible values: 'bad', 'poor', 'fair', 'good' and 'high'. The Directive requires that Water Bodies achieve or maintain at least *Good Ecological Status (GEcoS)*. This can be seen as an expression of EA05 and its "priority target" of "conservation of ecosystem structure and functioning".

WFD Annex V is long and provides details of how ecological status is to be evaluated using physico-chemical, hydromorphological, and biological, Quality Elements (table 5), the values of which are to be compared with those in *Type Specific Conditions (TSC)*. The latter have proven a source of difficulty when implementing the WFD, because types must be defined and their physico-chemical, hydromorphological and ecological conditions described. However, since accurately placing the quality boundary between 'fair' and 'good' is critical for water body management, this approach has the advantage of allowing the prescription of EQS (as I have defined them) that are highly relevant to local conditions.

Arguing the need for comparability across Water Body types and quality elements, the WFD (annex V.1.4.1) requires that evaluations be reported as *ecological quality ratios* (EQR), with values between 1 (perfect 'high' status) and 0 (worst 'bad' status). Thus, an ecosystem in which $\Delta S = 0$ (no change from TSC) would be evaluated at 1, while large values of ΔS would be evaluated with a lower quality ratio. Figure 4 illustrates this.

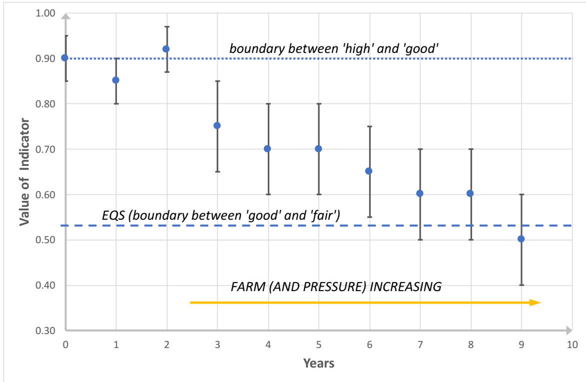

Figure 4: Figure 1 transformed, to illustrate the WFD approach. The indicator, Y% of samples exceed X μg chl L^{-1}, has been transformed into an EQR so that the value for 'normal', or *Type-Specific Conditions* (WFD 'high status'), converts to an EQR of 1.0, while Y% progressively higher than 'normal' maps to increasingly smaller values of the EQR, with 0 indicating 'bad' status. See Devlin et al. (2011) for examples relating to eutrophication.

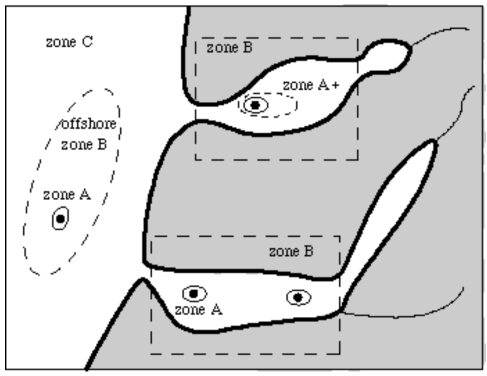

Figure 5: Scales, modified from fig 1.4 in Tett (2008).

6 Scales

EA07 states that the "approach should be undertaken at appropriate spatial and temporal scales". The scales to consider (in relation to aquaculture) are:

- those on which the natural environment might be significantly affected by a single farm, a group of farms, or an aquaculture industry;
- those of regions designated by society (e.g., in applying EU Directives) for management of aquatic ecosystems;
- those on which monitoring should take place.

Table 6 lists relevant scales. Let's start with those at which the effect of a single farm might be significant. Consider a net-pen fish farm in 50 m water depth. Uneaten food and fish faeces sink from the cages. Unless there are strong currents, the sinking matter will reach the seabed within minutes or hours and deposit over an area not much bigger than the farm. This begins to define the 'farm scale', *zone A*.

Next, imagine that a farm worker tips a basket of oranges into the water. The fruits serve as highly visible, nearly neutrally-buoyant, tracers of water motions. After half a day (or one cycle in most tidal waters) the distribution of the oranges defines the limits of zone A in the water column. Within this zone, concentrations of nutrients or dissolved oxygen might be obviously altered by the farm.

However, the consequences of additions such as nutrients will not appear quickly, because it takes a few days for phytoplankton biomass to develop. When it does, it will be distributed more widely than the zone A scale. Thus, the zone B scale is that mapped by the oranges after a few days have passed. In sheltered tidally-active waters their distribution will be

Table 6: Scales of effect, management, and monitoring, defined by natural and societal processes. ~ means 'about'; O means 'order (of magnitude) of'.

Scale	Description or Definition
CSTT zone A	around discharge or beneath farm; < 1 km, < 1 day
AZE	Allowable Zone of Effect beneath a farm
CSTT zone B	small water body or extended tidal ellipse; ~ 10 km, ~ 1 week
CSTT zone C	Boundary conditions for zone B
WFD Water Body	"discrete and significant element of surface water such as a lake, a reservoir, [all or part of] a stream, river or canal, a transitional water or a stretch of coastal water" (WFD 2.10)
AMA	Aquaculture Management Area (e.g. for disease control)
Marine Planning region	Depends on MSP regime; in Scotland ~ 100 km
Eco-hydro-dynamic domain	Pelagic habit of uniform physical properties , O $10^1 - 10^2$ km in Shelf Seas (van Leeuwen et al., 2015); needs definition for ocean basins
WFD River Basin District	"the area of land and sea, made up of one or more neighbouring river basins together with their associated groundwaters and coastal waters" (WFD 2.15)
MSFD Marine Sub-region	"designated for the purpose of facilitating implementation of [the MSFD] ...taking into account hydrological, oceanographic and biogeographic features;" (MSFD 3.2)
MSFD Marine Regions	Baltic Sea, North-East Atlantic Ocean; Mediterranean Sea; Black Sea

the result of tidal movement plus turbulent dispersion; in the open waters of the microtidal Mediterranean, wind and persistent currents will be the main drivers of dispersion. In certain cases, such as small estuaries, lagoons, rias and fjords, the zone B scale is defined by the basin itself, and could thus correspond to a WFD Water Body. See figure 5.

In some countries, regulators permit 'Allowable Zones of Effect', A-scale areas below or near farms in which substantial degradation of benthic ecosystem structure is allowed for finite periods, on the grounds that such AZEs comprise only a small part of a Water Body and that conditions within them are known to recover once the AZE is allowed to lie fallow. Of course, benthic monitoring is needed to ensure that this is the case.

An 'Aquaculture Management Area' may be designated for purposes of Marine Spatial Planning or to deal with the need to treat several farms at the same time for the prevention of disease (Adams et al., 2016; Aguilar-Manjarrez et al., 2017). Because the size of disease management areas depends on water motions, and (inversely) on the viability of disease organisms as they travel between farms, which is often a few days, AMAs often correspond to the zone B scale.

The UK Comprehensive Studies Task Team (CSTT), which named these scales, originally identified them in relation to waste-water discharges (CSTT, 1997), and saw 'zone C' simply as providing the 'boundary conditions' for zone B. These conditions are to be understood, simplistically, as things that can effect the State of the ecosystem in zone B, but which are not themselves affected by zone B. Clearly, however, farms can have a collective effect on a larger area of sea. Tett and Edwards (2003) considered whether the combined effects of salmon-farming on the West Coast of Scotland might increase the risk of 'undesirable disturbance' of 'the balance of organisms' in the phytoplankton in offshore waters (i.e. in zone C). Large areas of shellfish farming might deplete phytoplankton and suspended particulate matter in significant parts of sub-regional seas, which would increase the risk of MSFD QD4 (food webs) failing to be achieved.

Clearly, the matter of 'Scales' is a complex one, and at the large-scale end of the scale continuum involves societal as well as environmental issues, with Marine Spatial Planning being one of the available management tools (Aguilar-Manjarrez et al., 2017). At the small-scale end of the scale continuum – i.e. when devising an environmental management and monitoring programme for a single farm or small group of farms – managers and regulators need a good understanding of physical processes, biogeochemical processes, and biological community dynamics in the local sea and seabed. Initially this can be gained from textbooks (perhaps supplemented by local, non-scientific, knowledge as suggested by EA11), and subsequently improved by what is learnt during adaptive management.

7 Variability and Uncertainty

EA09 recognizes that ecosystems are variable in time and space. Such variability has practical consequences for management, because it adds uncertainty to indicator values and thus to decision making based on these values. Consider figure 1 again, reproduced here as figure 6. When does the time-series first transgress the EQS? Is it in year 3 or year 9?

In the diagram, the vertical bars indicate the confidence limits around the central values of the indicator. (These are the most probable values, in many cases the means or medians.) I assume: (1) that the sampling programme,

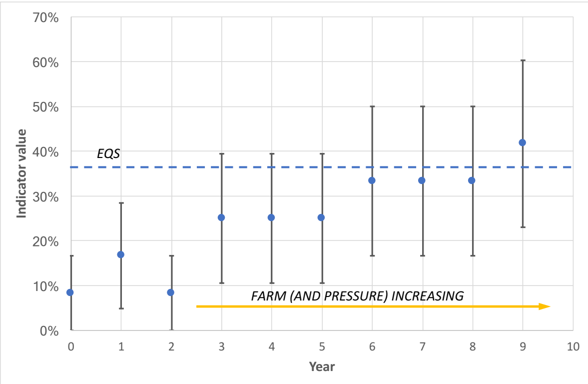

Figure 6: Uncertainty in measurement. (Figure 1 revisited.) Each estimate of an annual value of S includes a confidence interval: according to normal statistical practice, 19 out of 20 resamplings of each S would be expected to fall within the corresponding vertical bar. When does the time-series first transgress the EQS?

for the variables use to construct the indicator, has been well-designed to take account of temporal variability and spatial heterogeneity, so that the values obtained are representative of the ecosystem under investigation; and (2) that the resulting data have been analysed by reliable statistical methods to give confidence limits including 95% (or some other defined proportion) of possible values of the indicator in that year.

It is in year 3 that the confidence limits first overlap the EQS. A regulator applying the precautionary principle could (at the end of this year) argue that there is now some risk that the EQS is breached, and thus that restrictions be applied to the farm. However, it is only in year 9 that the central value exceeds the EQS, and so only in this year that it becomes more likely than not that a breach of the standard has taken place. Which interpretation to adopt is a matter that should, of course, be discussed and decided in advance.

Finally, there is the related matter of uncertainty in the EQS itself, uncertainty that arises not only from statistical aspects but also from societal decisions made about appropriate limits. Appendix B considers this issue for the example phytoplankton indicator. For a benthic example, see (Culhane et al., 2014) and in particular the parts dealing with statistical aspects of a comparison between different indicators of benthic ecosystem quality.

8 Conclusions

Designing a monitoring strategy starts by establishing well-specified EQO for the conservation of biodiversity and protection of ecosystem structure and function: I have illustrated this with the Qualitative Descriptors of the MSFD (table 3 and 4) and the Ecological Quality Elements of the WFD (table 5). The next step is to identify Pressures arising from aquaculture (table 2) and to determine the spatial and temporal scales on which they will bring about significant changes in the State of aquatic ecosystems, such as to give rise to a risk of failing the EQO. This will allow indicators of Pressure and State to be devised and a sampling plan implemented to obtain data from which to calculate indicator values.

Adaptive management can track changes in State indicators with time, as Pressures change. However, the most efficient adaptive management requires the preparation of Pressure-State relationships which, with suitable EQS and taking account of uncertainties, will allow managers or regulators to plan ahead for the development of farms or industries.

In the case of single farms it should be possible to use a small number of well-chosen indicators for cost-effective management and regulation; in this, adaptive management of farm effects contrasts with public management of WFD Water Bodies or MSFD subregions, which must deal with all components of GEcoS or GES. Such public management must also consider the aggregate effects of multiple farms (and perhaps other activities, such as hatcheries or processing plants) on Water Body or larger scales, and must assess this in relation to Pressures arising from other sectors of human activity.

Appendices

A Pressure and State: a systems view

This account uses the idea of an ecosystem as a spatially-bounded region which has a typical internal state $\mathbb{S}$ when in equilibrium with average boundary conditions $\mathbb{B}$. To these average conditions can be added a fluctuation $\Delta\mathbb{B}$, an anthropogenic Pressure $\mathbb{P}$, and their effects $\Delta\mathbb{S}$ on State. $\mathbb{P}$ is also a boundary condition: it is separately identified because its anthropogenic nature implies that it can be managed.[2]

The symbols $\mathbb{B}, \mathbb{P}, \mathbb{S}$ are to be understood in a somewhat fuzzy way, either as pointers to some 'real' things that can gives rise to the phenomena experienced by human observers, or as labels for constructs, such as scientific theories, that attempt to describe or explain these things. Management needs something more concrete, and this is provided by *indicators*, such as P and S, which are sets of numbers obtained by documented methods (of sampling and numerical manipulation) from the 'things in themselves'.

[2] The concept of a *Boundary Condition* (BC) comes out of applying analytical method as part of a Systems approach. Loosely speaking, a BC is something that affects a system but is not itself altered by changes within that system. To be more precise, let the system be partly described by a State Variable V (a hypothetical part of $\mathbb{S}$), which is a function of space x and time t:

$$\frac{\partial V}{\partial t} + \frac{\partial V}{\partial x} = f(t, x)$$

Solution of this equation will likely include at least two constants, the System initial condition $V(t = 0)$ and the Boundary Condition $V(x = 0)$. These are by definition not altered by system dynamics, but if $V(x = 0)$ is a Pressure, its value can be changed by management action.

The following scheme is a concise representation of the relationship amongst the 'things' and the indicators:

$$\begin{array}{ccccccccc} \mathbb{B} & + & \Delta\mathbb{B} & \& & \mathbb{P} & \Rightarrow & \mathbb{S} & + & \Delta\mathbb{S} \\ & & & & \downarrow & & & & \downarrow \\ & & & & P & \mapsto & & & \Delta S \end{array}$$

The arrow $\Rightarrow$ indicates a causal relationship 'in the real world', a relationship that scientists might try to elucidate in terms of testable hypotheses. The $\downarrow$ refers to the procedures used to get indicator values. The $\mapsto$ describes a mapping, a numerical relationship that allows values of ΔS to be estimated from values of P. The mapping might be purely empirical, for example based on regressing sets of ΔS on sets of P, or it might have a mechanistic base in hypotheses about the causal relationship in the 'real' world.

The operator & is meant to suggest that $\mathbb{B}$ and $\mathbb{P}$ combine in a complex way, which is possibly unknown but could potentially be understood by scientific investigation. The operator + has something close to its usual meaning (for array addition). Thus $\mathbb{B}+\Delta\mathbb{B}$ is to be understood as saying that (at least for small changes) a change in boundary condition simply adds to (or subtracts from) the average condition. And analogously for $\mathbb{S}+\Delta\mathbb{S}$.

This mathematical shorthand can be made more concrete with an example. Let the ecosystem in question be a lagoon used for shellfish cultivation. Its Boundary Conditions (BC) include (i) concentrations of nutrients and phytoplankton in the sea-water exchanging with, the lagoon; and (ii) the sunshine falling on the lagoon's surface. The BC have typical values but can vary from day to day or year to year. These conditions, plus the internal dynamics of the lagoonal ecosystem, are what causes or gives rise to the State of the system in the absence of mariculture.

The shellfish farm is seen as external to the lagoonal ecosystem, i.e. lying outside its boundary, and thus as withdrawing phytoplankton (eaten by the shellfish) from the system whilst introducing nutrients and faeces into it. Thus these effects are seen as boundary conditions in general but specifically as a Pressure, because the farm is under human control, and can be regulated.

In contrast, the filter-feeding activity of normal members of the benthic community is seen as a process within the ecosystem. Were these 'wild' shellfish to be harvested, the Pressure would be the human harvesting activity, not the shellfishes' consumption of phytoplankton.

Suppose that the size of the shellfish farm changes from year to year, thus changing the Pressure. Suppose that monitoring gives annual values of mean phytoplankton biomass, from which a State indicator could be constructed as the excess of the observed biomass (in each year) over the 'normal' value (that in the absence of significant local anthropogenic pressures.) A mapping $P \mapsto \Delta S$ could be made in order to aid management of the farm's effects on the ecosystem. Perhaps the mapping would be a simple linear regession with zero intercept, $\Delta S = -m \cdot P$. The estimate of the coefficient m might be in error for several reasons that include both sampling error and the effect (unrecognized in the regression) of the variability ΔB, with consequences for management discussed in section 7.

Finally, the scheme set out here assumes that the ecosystem responds at once to changes in Boundary Conditions and Pressure. Where there are lags (O'Higgins et al., 2014), a better model might be:

$$\mathbb{B} + \Delta\mathbb{B} \;\&\; \mathbb{P} \;\&\; \mathbb{S}_{-T} \;\Rightarrow \mathbb{S} + \Delta\mathbb{S}$$

where $\mathbb{S}_{-T}$ refers to an earlier State. In this case, time-series of S might show autocorrelation, $P \mapsto S$ graph might show hysteresis, and there will be more difficult to predict the conditions under which an EQS will be transgressed.

B Variability example

The variability of ecosystems will be illustrated here, for the pelagic habitat, with findings (figure 7) from a small Scottish fjord, loch Creran, which has been sampled intermittently since 1972 (Tett and Wallis, 1978; Whyte et al., 2017).

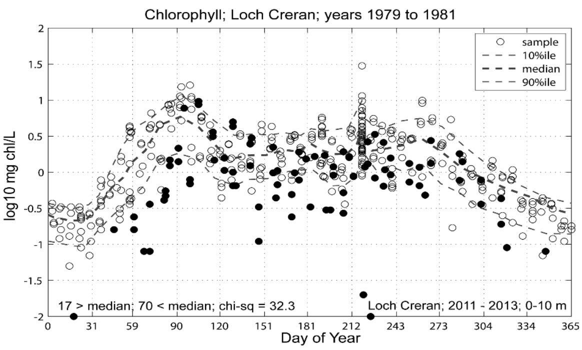

Figure 7: Variability in chlorophyll in Loch Creran, from Whyte et al. (2017, SM). Each point is plotted from a single water sample. The dashed lines form an envelope enclosing 90% of the observations made during 1979 - 1981 (open circles). Observations 2011 - 2013 are plotted as filled circles.

The diagram shows chlorophyll concentrations measured in individual water samples. The concentrations are plotted on a logarithmic scale, in order to show the range of variation (up to 4 orders of magnitude) in the phytoplankton. Several kinds of variability are apparent: (1) seasonal changes within a typical year, indicated by the envelope of dashed lines fitted to the observations made between 1979 and 1981; (2) variability observed in different parts of the water body on the same day, and between the same day in different years; and (3) the changes in the amounts of chlorophyll and the seasonal pattern between 1979 - 81 and 2011 - 13.

Table 7: Chlorophyll statistics. N is number of samples, N>10 is number of samples exceeding 10 μg chl/L.

year	N	N > 10	%
1979	234	9	4%
1980	115	1	1%
1981	174	20	11%
2011-13	87	1	1%

These data can be used with the phytoplankton indicator used as an example in this essay. The indicator's value for a given year is the percentage of samples exceeding concentration X'. In the case of Loch Creran, a bloom is deemed to occur for $X = 10\mu$g/L, a value arrived at by 'expert judgement'.

I was the expert, in this case serving on the UK Comprehensive Studies Task Team between 1992 and 1997 (CSTT, 1997). My reasoning was based on the envelope of chlorophyll in loch Creran published earlier (Tett and Wallis, 1978), the argument that the loch was not anthropogenically enriched, and on the recognition that chlorophyll concentrations greater than this figure would visibly discolour the sea.

The corresponding EQS is of the type 'Y% of samples exceed X'. So how to find a value for Y? According to an EU WFD working group WFD (COAST, 2003), the 'natural' value of Y could be estimated by observing a Water Body under minimal anthropogenic Pressure and thus exhibiting the 'type-specific conditions'. Creran was (we thought) minimally pressured between 1979 and 1981, and so could be use to to define the TSC for this type of fjord. The observed percentage of samples exceeding 10 μg chl/L was between 1% and 11% in these three years (table 7). So it might be reasonable to use a value of Y of, say, 15%, in the EQS.

However, if only 12 annual samples were available, it is possible that 2 of them might have been taken during the natural Spring bloom, corresponding to Y of 17%. Thus, if we wish to avoid 'false alarms', it might be better to set the EQS higher, to, say, 20%.

Finally, why have I used this indicator of State as my example? Why did I not suggest using the average concentration of chlorophyll found in water samples? Inspection of figure 7 will show that the average is likely both to be arduous to determine and to have a large confidence interval - at least in the case of the Scottish coastal waters with which I am familiar. More particularly, however, the indicator used here was made with monitoring of the 'bloom frequency and intensity' component of the Phytoplankton BQE of the WFD (table 5) in mind. It allows me to emphasise that indicators are quantities constructed for management purposes and devised in relation to particular EQO. They are not to be mistaken for the 'real things' that they point to.

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