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Review of broad-scale environmental monitoring programs: Huon Estuary and D'Entrecasteaux Channel

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Acronyms & Abbreviations

AMBI	AZTI - Marine Biotic index
AST	Analytical Services Tasmania
B	Bottom
BACI	Before-After-Control-Impact
BQE	Biological Quality Elements
BQI	Benthic Quality Index
BEMP	Broad-scale Environmental Monitoring Program
CSIRO	Commonwealth Scientific and Industrial Research Organisation
HEDC	Huon Estuary and D'Entrecasteaux Channel
DIN	Dissolved Inorganic Nitrogen (the sum of NO and NH but excluding N_2)
DIP	Dissolved Inorganic Phosphorus (mostly, phosphate ions)
DO	Dissolved Oxygen
DRP	Dissolved Reactive Phosphorus (roughly equivalent to DIP)
DSi	Dissolved Silica
DSP	Diarrhetic Shellfish Poisoning
DPSIR model	Chain of linkages between the Driving forces within society (D), the Pressure on the environment (P), the State of the environment itself (S), the Impact on people and nature (I) and the desirable Response (R)
ECE	Equilibrium Concentration Enhancement
EPA	Environment Protection Authority
ES	Enrichment Stage
GES	Good Ecological Status (WFD) or Good Environmental Status (MSFD)
HE	Huon Estuary
HPLC	High Performance Liquid Chromatography
IMAS	Institute for Marine and Antarctic Studies
IR-GCMS	Isotope ratio Gas chromatography Mass spectrometry
ITI	Infaunal Trophic Index
LIST	Land Information System Tasmania
MDS	Multi-Dimensional Scaling plots
MFDP	Marine Farming Development Plan
MSFD	Marine Strategy Framework Directive
MPA	Marine Protected Area
NDC	Northern D'Entrecasteaux Channel
NH	Reduced Nitrogen: dissolved Ammonia + Ammonium ions
NO	Oxidised Nitrogen – here referring to the ions Nitrate and Nitrite
POM	Particulate Organic Matter
PSP	Paralytic Shellfish Poisoning
QD	Qualitative Descriptors
ROV	Remote Operated Vehicle
RVA	Rapid Visual Assessment
S	Surface
SAMS	Scottish Association for Marine Science
SDC	Southern D'Entrecasteaux Channel
TAN	Total Ammoniacal Nitrogen, equivalent to NH in this report
TN	Total Nitrogen (measured after Kjeldahl digestion)
TSGA	Tasmanian Salmonid Growers Association
WFD	Water Framework Directive

0. EXECUTIVE SUMMARY

SAMS Applied Marine Science Enterprise Ltd. (SAMS Enterprise), was commissioned by the Tasmanian Environment Protection Authority (EPA) to conduct a review of the Broad-scale Environmental Monitoring Program (BEMP) undertaken in the Huon Estuary and D'Entrecasteaux Channel (HEDC) Marine Farming Development Plan (MFDP) area. The aim of the HEDC BEMP is the detection of salmonid-farming related effects within HEDC ecosystems considered on the broad scale of the MFDP area rather than in the immediate vicinity of fish farms.

By reviewing papers and reports and also receiving representation from stakeholders, our task has been to determine the question: "*Is the BEMP likely to be effective in detecting salmonid farming related broad-scale ecosystem effects within the MFDP area?*" and then to recommend solutions to any deficiencies and improvements to any inefficiencies.

The BEMP has provided a unique and valuable decade-long time-series of water and sediment quality variables that allows the tracking of potential change in ecosystem State in response to exogenous Pressures such as climate change in addition to responses to the endogenous and manageable Pressure of fish-farming. Distinguishing between endogenous and exogenous Pressures reduces the risk that fish-farming will be blamed for changes for which it is not responsible.

Current management relies on trigger levels established by Thompson et al. (2008) for a small set of water quality variables, especially concentrations of ammonia, chlorophyll and dissolved oxygen, and for the sediment chemistry variables redox potential and sulphide concentration. We recommend that more attention is paid to the State of the main pelagic and benthic habitats that, together with populations of mobile species such as fish, marine mammals and seabirds, make up the ecosystem of the HEDC. Considerable sampling effort has been directed to obtaining information about the floristic composition of the phytoplankton and the faunistic composition of soft-sediment benthos, but little use has so far been made of this information. We recommend adoption of a 'balance of organisms' indicator to track year-to-year changes in phytoplankton floristic composition and a range of standard benthic indicators for benthic faunal composition to complement the present multivariate approach.

Additionally, we think that the current monitoring of epiphytes in seagrass and hard-bottom benthic habitats/communities, should become part of the BEMP.

Pelagic Habitats

On the 'broad scale' addressed by the BEMP, where water residence times are a week or more, farm-produced reduced nitrogen (NH: Ammonia/Ammonium ion) is likely to be mostly converted to nitrate or into phytoplankton and higher trophic levels within a day or two. NH observed on this scale might have several original sources in addition to fish farms. We therefore do not believe that NH is a good indicator of fish farm nitrogen emissions at the broad scale. Instead the key nitrogen parameter should be Dissolved Inorganic Nitrogen which sums ammonia-N with oxidised nitrogen (nitrate and nitrite).

We propose a new statistical analysis be made of existing BEMP data to better understand sources of variability and potential to detect change: A critical challenge is to identify the anthropogenic component amidst the high spatial and temporal variability in nutrient and chlorophyll concentration. We suggest the need for a more sophisticated statistical analysis, possibly a

Generalised Additive Model (GAM) of the spatial and temporal components of variability in main indicators in the HEDC system.

The results of this statistical analysis should be used to evaluate the current sampling strategy with a view to reducing number of sampling sites. Given that existing analyses show high within site variability compared with between-site variability in chlorophyll, it may be that it will be sufficient to maintain one BEMP site in each of the Huon Estuary, the northern D'Entrecasteaux Channel, the southern D'Entrecasteaux Channel, and an open-sea boundary condition site. At the same time sampling frequency should be increased, for example by adding instrumented moorings for chlorophyll. Telemetering information from such moorings could be used to trigger additional phytoplankton sampling during bloom events.

So far as the 'balance of organisms is concerned', the diatom-dominated phytoplankton community in HEDC seems generally as expected for temperate coastal waters with low ambient N and P and enriched in Si by river discharge. Application of life-form based analysis tools is recommended to confirm this diagnosis.

Benthic Habitats

The benthic and sediment monitoring reveals no great changes overall and certainly nothing that could be attributed to the fish farming industry. This may be the case regardless of where the benthic/sediment stations are sited outside the immediate area of the farms. However, the sampling stations were not originally selected to maximise the chance of observing subtle effects, should they be present. We recommend that a study is conducted to place benthic/sediment monitoring stations in optimal locations and to discard stations which currently have little prospect of detecting any long-term changes that may be caused by fish farming. Several of the present stations in the most promising locations (i.e. with high proportion of fine particles) should be retained so as to maintain continuity of the time series. Stations with low proportions of fines should be discarded from future surveys.

A study should be carried out to identify the most likely places in the domain that sediments will accumulate. Candidate sites should be evaluated with a field survey focussing on particle size and total organic carbon. Hopefully, this will allow stations to be added to the BEMP that have the best possible chance of detecting broadscale effects from fish farming. A few of the softest stations identified should be selected and some long cores taken for establishment of the accumulation rate by dating and to determine if there is a biogeochemical signal that can be linked to the growth of the fish farming industry.

The advantages of moving towards a DNA metabarcoding methodology for infauna in terms of data-richness, cost and speed should be investigated.

Modelling

The hydrodynamic and biogeochemical models developed by CSIRO and applied to the HEDC complement the observational BEMP. They have provided an understanding of the hydrodynamics of the water bodies, helped design the BEMP sampling strategy, and been used for an investigation of the probable consequences of nitrogen inputs in excess of the regulatory cap. They should continue to be used for diagnosis and prognosis.

1. INTRODUCTION

1.1. Project Background

SAMS Applied Marine Science Enterprise Ltd. (trading as SAMS Enterprise), was commissioned by the Tasmanian Environment Protection Authority (EPA) to conduct a review of the Broad-scale Environmental Monitoring Programs (BEMPs) undertaken across multiple Marine Farming Development Plan (MFDP) areas, including the Huon Estuary and D'Entrecasteaux Channel, Macquarie Harbour, and Storm Bay regions of Tasmania, to monitor ecological condition at the whole ecosystem level in response to marine fish farming in the same water bodies.

Task 1:
Comprehensive desktop reviews for each site will evaluate the suitability and efficacy of the broad suite of physical, chemical and biological parameters collected as part of the monitoring programs, together with spatial and temporal sampling scales to assess ecological change in the context of intensive salmon farming.

Task 2:

Stakeholder engagement with the Tasmanian aquaculture industry technical specialists and other scientific specialists, including at the Institute for Marine and Antarctic Studies at the University of Tasmania (IMAS), CSIRO and other relevant scientific institutions, will be undertaken to both inform the BEMP review and to demonstrate the EPA's transparency in the process.

Task 3:

The reviews will provide recommendations to the Director (EPA) on the efficacy of the respective Broad-scale Environmental Monitoring Programs in detecting spatial and temporal trends for key environmental parameters and allowing broad-scale assessment of the environmental effects of salmon farming. The reviewers' recommendations will be informed by the outputs of tasks 1 and 2 and, in particular, by their answer to the key question "*Are the monitoring frameworks within the BEMPs likely to be effective in detecting salmonid farming related broad-scale ecosystem effects within their respective MFDP areas?*"

- If the answer is in the negative, deficiencies of the current monitoring programs will be identified, and a list of detailed recommendations will be provided on how to modify BEMPs to ensure that they can effectively detect any salmonid farming related broadscale ecosystem effects within their respective MFDP areas. The justification underlying any recommendations will also be provided.
- If the answer is in the affirmative, the reviewers will assess if there are opportunities to modernise the current monitoring program to improve sampling efficiency and cost effectiveness whilst maintaining the goal of the monitoring program to detect salmonid farming related broadscale ecosystem effects within their respective MFDP areas. A list of detailed recommendations will be provided on how to rationalise BEMPs. The justification underlying any recommendations will also be provided.

1.2. Document Purpose

The review is divided into three stages:

- **Stage 1: Huon Estuary and D'Entrecasteaux Channel**
- Stage 2: Macquarie Harbour
- Stage 3: Storm Bay Region

This report is for stage 1, Huon Estuary and D'Entrecasteaux Channel. We use the joint acronym HEDC. The report is divided into two main sections dealing firstly with aspects relating to the water column monitoring and secondly with aspects relating to the monitoring of the sediments and benthos. A final section summarises recommendations.

In this review we have used results from BEMP, earlier studies, and modelling, to better understand the HEDC system, the impact that fish-farming might have on the ecosystem as a whole, and the best way to monitor that impact in order to take action if necessary. Figure 1 maps our understanding of the BEMP's pelagic components as they have evolved. We have also been informed by recent scientific advances and by shifts in approaches to water quality regulation/management. Table 1 compares the principles of the Australian and New Zealand Guidelines for water quality with those of two European aquatic environmental protection directives which have influenced our thinking. Our focus in the review has been the BEMP and associated research projects, and we have not considered other aspects of aquaculture-environment interaction such as escapes, parasites, medicines or other chemicals such as disinfectants.

We have consulted with various stakeholders including government agencies, fish farmers, academics, consultants and environmental interests. They are listed in Appendix 1. Although our recommendations are our own, we are grateful to those who have provided much valuable and informative comment. We are grateful to Aquenal pty for permission to reproduce diagrams from Aquenal (2020).

We are not aware of any other fish farming country or region carrying out a broad scale environmental monitoring programme at the scale undertaken here. The decision by the Tasmanian authorities to develop with industry a programme of industry-funded broad scale monitoring as the industry developed was both laudable and prescient.

*Research on far-field and regional processes, especially in intensively farmed areas and over longer time scales, will refine understanding of the full ecological role of fish farms in marine environments (*Price et al., 2015).

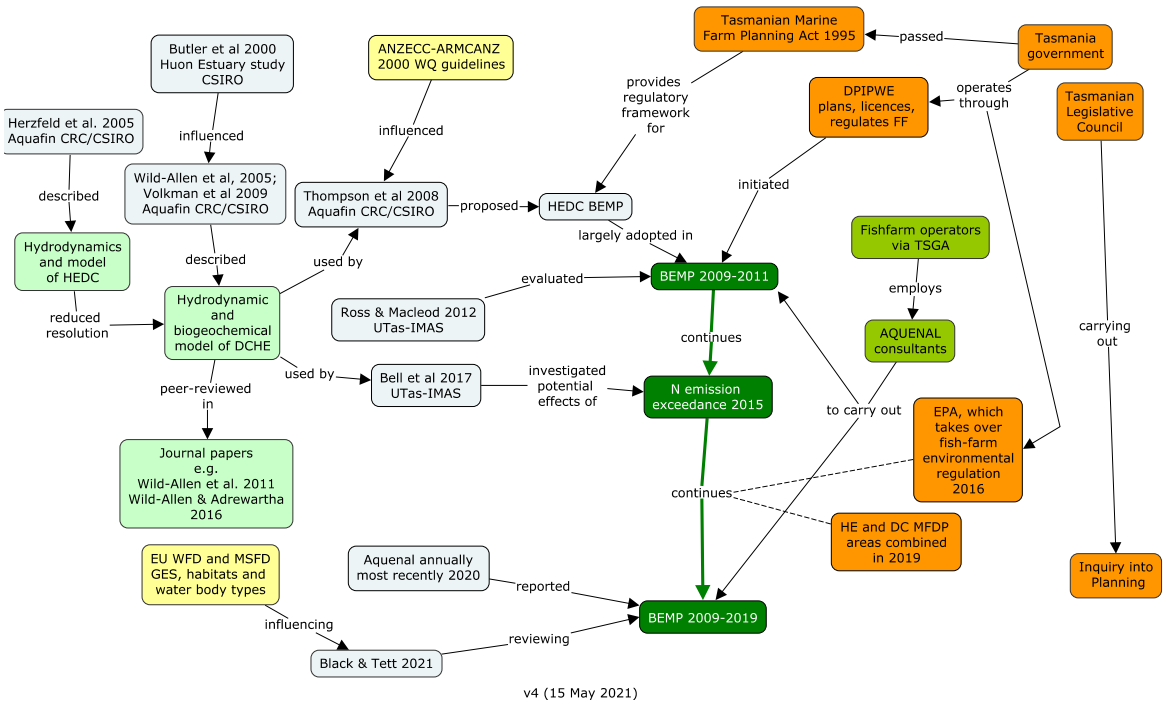

Figure 1: Conceptual map showing the evolution of the pelagic component of the HEDC BEMP in relation to key publications considered in section 2. The BEMP annual reports by Aquenal use 12-month periods starting in March one year and ending in February the next year; for example, Aquenal (2020) reported what we will call the 2019 BEMP, ending in February 2020.

1.3. Definitions of pelagic and benthic habitats

The term 'pelagic habitat' is used to refer to the physical and chemical environment of the water column together with the drifting organisms of the plankton that inhabit it. Benthic habitats are those of the sea-bed and the communities of sedentary organisms associated with particular types of seabed. Populations of mobile animals, including fish and sea-birds, make use of these habitats but are not included in them.

Because of the differing dynamics of pelagic and benthic environments and communities, the sampling and measurements regime for pelagic habitats is quite different from that of the benthic habitats, and so the two types of habitat are dealt with separately in the next part of this review.

1.4. The BEMP

The existing Broad-Scale Environmental Monitoring Program (BEMP) is largely the result of proposals by Thompson et al. (2008) for what were, at the time, two Marine Farming Development Plan (MFDP) areas. One covered the lower Huon Estuary, the other the D'Entrecasteaux Channel. The two plan areas were combined in October 2019 to make the HEDC (Huon Estuary and D'Entrecasteaux Channel) MFDP area.

An obligation to carry out specified sampling is contained in the environmental licences issued for each farm site ("finfish growing operation") in the MFDP plan area(s), and this obligation has so far been discharged collectively by the farming companies acting through the TSGA to employ

Aquenal pty to sample, commission analyses, and report. The BEMP was commenced in March 2009, was reviewed by Ross & Macleod (2013) and was most recently reported (up to February 2020) by Aquenal (2020).

Table 1: Comparison of management frameworks for aquatic environmental quality

Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000)	EU Water Framework Directive (2000)	EU Marine Strategy Framework Directive (2008)
"primarily based on the philosophy of ecologically sustainable development …, [defined as development] using, conserving and enhancing the community's resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future can be increased. …	Aims *inter alia* at restoring or maintaining Good Ecological Status (GES) in Water Bodies as part of River Basins (including coastal waters), where Ecological Status is "an expression of the quality of the structure and functioning of aquatic ecosystems .. classified in accordance with Annex V"	Aim is to achieve or maintain Good Environmental Status (GEnvS) in member states EEZ on the scale of (large) marine sub-regions. GEnvS is 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, thus safeguarding the potential for uses and activities by current and future generations…"
require "clearly stated set of environmental values … [which] are particular values or uses of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health and which require protection from the effects of pollution, waste discharges and deposits. …" They include "ecosystems", biophysical resources directly used by primary industries including fish products, "recreation and aesthetics", and "cultural and spiritual values"	A Water Body achieves GES when the state of several Biological Quality Elements (BQE) differs little from those in a water body of the same type that is experiencing minimal human disturbance (a Type-Specific Reference Condition, TSRC). BQE for coastal waters are those for phytoplankton, macroalgae and angiosperms, and benthic invertebrate fauna. Although not specified in the Directive, it has become usual to combine BQE values on a 'one-out, all-out' basis.	GEnvS is determined by 11 Qualitative Descriptors (MSFD Annex I), of which most relevant are: QD1: "Biological Diversity is maintained" (including according to COM (2017) the quality and extent of the main pelagic and benthic habitats/ communities); QD4: "All elements of food webs … occur at normal abundance and diversity .." QD5: "Human-induced eutrophication is minimised…" QD6: "Sea-floor integrity is at a level that .. ensures benthic ecosystems ..are not adversely affected."
Management framework has following steps 1. define management aims 2. determine water quality guidelines 3. define water quality objectives 4. establish monitoring and assessment program 5. if necessary, initiate management response	Management framework requires 1. identification and typing of water bodies 2. establishment of a monitoring programme including relevant BQE (and other) indicators calibrated against TSRC 3. establishment of programme of measures to improve water body status if not Good. Operationally, WQO set by values of BQE at GES threshold.	Management framework requires 1. establishment of "a comprehensive set of environmental targets and associated indicators" 2. establishment of monitoring programmes (co-ordinated between member states) 3. identification and implementation of (socially and economically cost-effective) programmes of measures to improve marine environment status if not Good.

2. THE PELAGIC HABITATS

2.1. Mechanisms of interaction between marine cage fish farms and pelagic habitats at the basin scale

2.1.1. Eutrophication

Marine photosynthetic organisms – the micro-algae and blue-green bacteria of the phytoplankton, and the benthic macro-algae (seaweeds) and sea-grasses – take energy from sunlight in order to make organic compounds from carbon dioxide dissolved in sea-water. In addition, they need plant nutrients, which are compounds of nitrogen and phosphorus, to complete the synthesis of proteins and nucleic acids. In many parts of the sea these plant nutrients are scarce, and adding them can lead to enhanced growth of phytoplankton and seaweeds (but not of sea-grasses, which take nutrients from the sediments in which they grow). If such stimulation is excessive, the result is eutrophication, defined by Ferreira et al. (2011) as "*enrichment of water by nutrients, especially compounds of nitrogen and phosphorus, leading to enhanced growth, primary production and biomass of algae, [and consequentially] leading to changes in the balance of organisms and water quality degradation*".

Fish excrete dissolved compounds of nitrogen and phosphorus through their gills, and further amounts of nitrogen and phosphorus compounds are released when fish faeces and other organic matter decay on the sea-bed. Thus, an early concern in the development of sea-cage fish-farming was the potential of nutrients released by caged fish to cause eutrophication (Gowen & Bradbury, 1987). In designing what became the BEMP, Thompson et al. (2008) identified the *"most significant threats to the ecological functioning of the D'Entrecasteaux Channel and the Huon Estuary ecosystem [as] further increases of organic matter and nutrient inputs (eutrophication). The most common symptoms of eutrophication include increased nutrient concentrations, trophic decoupling, increased algal blooms, hypoxia, changes in nutrient cycling, reductions in water clarity, eventual loss of benthic macroflora, changes in food web structure and organic enrichment of the bottom waters and sediments, and/or changes in benthic fauna and microbial processes."* In our view, it is useful to distinguish direct organic enrichment by farm solid waste, which mainly impacts close to a farm except in regions of strong water currents, from the consequences of nutrient enrichment. The direct effects of this nutrient enrichment in stimulating production by phytoplankton and seaweeds may lead to a secondary increase in organic matter reaching the sea-bed.

Over the decades there have been some changes in the way in which water quality regulation has framed marine eutrophication (we write here about the European situation, with which we are most familiar). Prior to 2000, and still evident in the OSlo-PARis convention (OSPAR)'s 'Strategy to Combat Eutrophication' (OSPAR, 2003) is a conceptual model of nutrients as a form of pollution. According to OSPAR's 'comprehensive procedure', marine areas can be designated as eutrophic (and therefore as 'problem areas') on the basis of enhanced concentrations of nutrients during Winter, enhanced concentrations of chlorophyll during the phytoplankton growing season in Spring and Summer, and deficiencies in dissolved oxygen. The Scottish 'Locational Guidelines' for the siting of fish-farms consider (so far as the water column is concerned) only the potential of farm-derived nutrients to increase the 'equilibrium concentration' of nutrients in a water body

(Gillibrand et. al., 2002), the implicit assumption being that the outcome to be avoided is the complete conversion of this nutrient into phytoplankton.

In 2000, the EU Water Framework Directive (2000/60/EC) (WFD) introduced the concept of the 'Ecological Quality Status' of water bodies, this being determined by the extent to which certain 'Biological Quality Elements' (BQE) deviated from the 'Reference Conditions' supposed typical of a water body of the same hydrochemical type suffering minimum human disturbance. The management target of 'good status' was defined, for the phytoplankton BQE in coastal waters, as occurring when "*the composition and abundance of phytoplanktonic taxa show [only] slight signs of disturbance. There are slight changes in biomass compared to type-specific conditions. 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. [Only] a slight increase in the frequency and intensity of the type-specific planktonic blooms may occur.*"[1]

In 2008 the EU Marine Strategy Framework Directive (2008/56/EC) (MSFD) expanded the status concept by requiring member states to aim for 'Good Environmental Status (GES)' defined by 11 'Qualitative Descriptors' (QD). Although 'Eutrophication' was QD number 5, it was understood (Borja et al., 2010) as a Pressure on the State of marine ecosystems, this State being diagnosed with the aid of QD1, 'Biodiversity' and QD4, 'Food Webs'. In essence, biodiversity and food web structure had to be such as to permit ecosystems to function fully. In the case of food webs this requires a proper balance amongst the main trophic groups, and in the case of biodiversity requires (COM, 2017) that, for each 'pelagic broad habitat type', the "*condition of the habitat type, including its biotic and abiotic structure and its functions (e.g. its typical species composition and their relative abundance, absence of particularly sensitive or fragile species or species providing a key function, size structure of species), is not adversely affected due to anthropogenic pressures*."[2]

Thus, best practice in marine environmental monitoring now includes the tracking of indicators of the State of the main pelagic habitats (e.g. McQuatters-Gollop et al., 2019) and, if deviations from good status are observed, the explanation of these deviations in terms of exogenous and endogenous Pressures (Elliott, 2011), leading to appropriate remedial action.[3] In the present context, an example exogenous Pressure is that resulting from global climate change, which although at least partly human-caused, cannot be locally managed; and the relevant endogenous Pressure, which can be managed, is input of nutrients from fish-farms and other anthropogenic sources.

2.1.2. The pelagic environment of the Huon Estuary and D'Entrecasteaux Channel

The area of the HEDC defined for the BEMP and MFDP provides conditions in which fish-farm nutrients have the potential to stimulate the growth of phytoplankters during the part of the year when sufficient sunlight penetrates the upper waters of this area. In addition to anthropogenic

[1] The other BQE concern 'macroalgae and angiosperms' and 'benthic invertebrate fauna'.

[2] There is a similar requirement for the main benthic habitats.

[3] We capitalise the initial letters of Pressure and State in reference to the DPSIR model of the "chain of linkages between the driving forces within society (D), the pressure on the environment (P), the state of the environment itself (S), the impact on people and nature (I) and the desirable response (R)" (Luiten, 1999; see also Elliott et al., 2017).

sources, nutrients are also supplied from the open sea and rivers (especially the Huon River). Thus, the contribution of farm nutrients to increased phytoplankton biomass and to broad-scale ecosystem disturbance must be assessed against fluctuations in nutrients and plankton resulting from natural variability of river discharges and of marine inflows. Based on observations and hydrodynamic modelling, Herzfeld et al. (2005) summarised (Figure 2) "*the conceptual model of residual flow for the D'Entrecasteaux – Huon Estuary system … as follows: flow enters the region in bottom water at the southern end of the channel and continues along the bottom and upstream into the Huon Estuary in the salt wedge, favouring the southern bank. Entrainment occurs from the salt wedge into the downstream freshwater flow, the majority of which then turns north upon entering the channel and exits into Storm Bay at the northern end of the channel. A smaller proportion of Huon flow exits the southern channel.*"

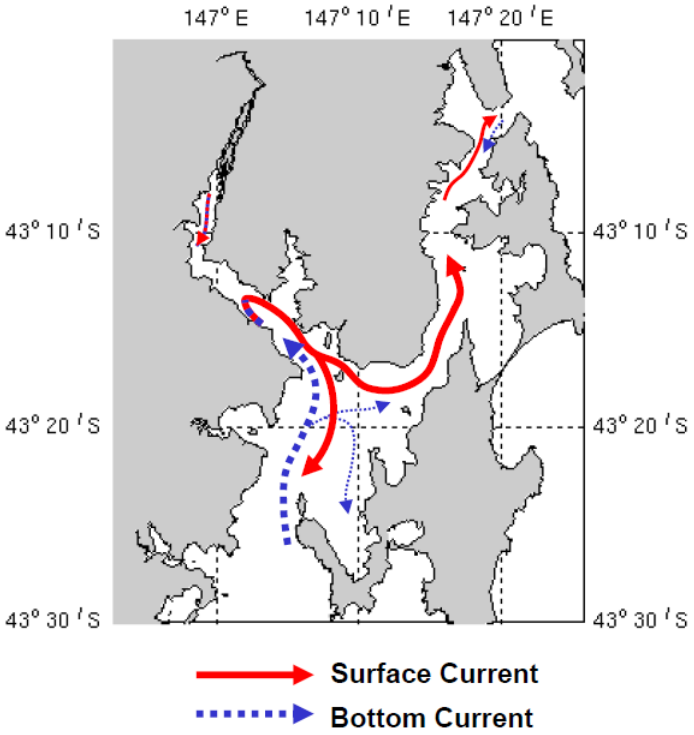

Figure 2: Map showing residual circulation according to Herzfeld et al. (2005, fig 95) – fig. 2-7 in Ross & Macleod (2013). Used with permission from M. Herzfeld.

Point source nutrient inputs, such as those from fish-farms, are dispersed by the combination of HEDC's large-scale residual circulation and smaller-scale eddy mixing. Furthermore, these water movements also disperse phytoplankters that may have absorbed nutrients near farms. Thus, although some studies in several parts of the world have observed local enhancement of nutrients (especially ammonia) near fish-cages (Price et al., 2015), very few have been able to detect local increases in phytoplankton biomass or local changes in the balance of organisms.[4]

[4] Price et al. (2015) review some studies reporting significant increases in algal biomass or production near farms. However, these involved either fixed seaweeds or, in one case, micro-algae retained in bags made of semi-permeable membrane (Pitta et al., 2009).

2.1.3. Nutrient budgets

There are two epistemological challenges to 'broad-scale' monitoring: the first concerns the detection of persistent change in the State of the plankton against a background of natural fluctuations; the second, the need to relate such changes, if observed, to anthropogenic (especially fish-farm) nutrients.

The severity of the second challenge is inversely proportional to the contribution of fish farm nutrients to the total budget for the water body. Butler et al. (2000) concluded that farms in the Huon estuary contributed about 2% of the nitrogen supply, and about 3% of the phosphorus supply, in 1996-1998. Such effects would be very hard to detect. In a modelling study of a region that included the Derwent estuary as well as the HEDC, Wild-Allen & Andrewartha (2016) concluded that in 2009, fish farms in the Huon Estuary contributed a more significant 34% of nitrogen supply there, while those in the Channel contributed 35%. The other main sources were rivers and the sea (Figure 3).

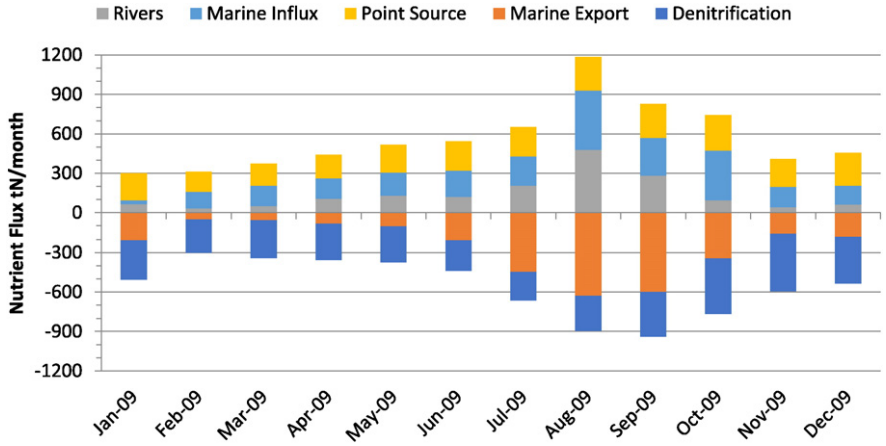

Figure 3: Nitrogen fluxes in (+) and out (-) of the region simulated by Wild-Allen & Andrewartha (2016, fig 6), which included the Derwent estuary as well as the HEDC. Although other anthropogenic point-sources contribute to the Derwent budget, fluxes in the D'Entrecasteaux Channel are dominant overall. Used with permission from K. Wild-Allen.

2.1.4. Spatial scales and the nitrogen cycle

Reduced nitrogen (NH) in the form of dissolved ammonia or ammonium ions is the main route for N excretion by farmed fish, and concentrations of NH are often observed to be higher near fish farms. However, this NH is not expected to persist for long, because it is oxidised to NO (nitrite or nitrate ions) by chemo-autotrophic micro-organisms or (during the algal growing season) assimilated by phytoplankters and seaweeds.

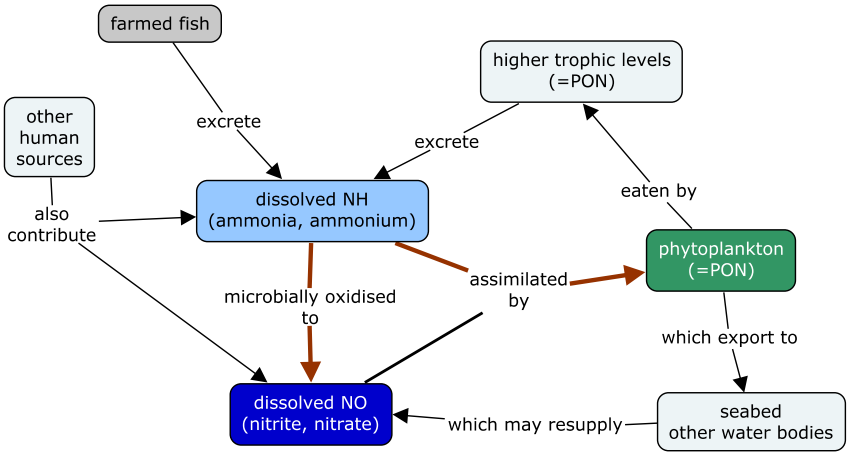

Figure 4: The transformations experienced by nitrogen compounds excreted by farmed fish.

The chemo-autotrophs are bacteria and archaea that oxidise NH to nitrite and bacteria that oxidise nitrite to nitrate (Zehr & Kudela, 2011). Rates of these microbial processes are reported as low in oligotrophic environments (e.g. Clark et al., 2008), but both absolute and relative rates appear to speed up under conditions of NH enrichment. For example: pelagic micro-organisms nitrified up to 70% of daily additions of ammonium in microcosms that replicated conditions in Naragansett Bay (Berounsky & Nixon, 1985); during Winter, nitrification rates in NH-rich Dutch coastal waters ranged from 1 to 5 µM day (Veuger et al., 2013); and McLaughlin et al. (2017) concluded that much of the waste-water ammonium discharged into low-nutrient Californian waters was converted to nitrate on a 1-day timescale

Thus, on the 'broad scale' addressed by the BEMP, where water residence times are a week or more, observed NH is less likely to have originated directly from farms and more likely to have come from excretion of NH by pelagic or benthic animals that have fed on phytoplankton or POM. And thus DIN (Dissolved Inorganic Nitrogen, the sum of NH and NO) concentration (but excluding N_2) is likely to be better than NH as a measure of the free nutrient available to stimulate the growth of phytoplankters or seaweeds on the broad scale monitored by the BEMP. On intermediate scales, defined by the distance that water moves within a day of passing a fish farm, observed NH may be mostly that added by a farm.

During the phytoplankton growing season, and on the broad scale, most DIN has been assimilated by phytoplankters and its nitrogen trophically transferred to zooplankters and POM (Figure 4). Total Labile Nitrogen (TLN) is the sum of such particulate nitrogen plus DIN and any other low-molecular-weight nitrogen compounds. Together with nitrogen transferred to the benthos and sediments, it is what is available locally to replenish DIN levels during Winter. In principle, comparing TLN in the presence of fish farms with that observed under reference conditions would be a good way to confirm the enrichment. In practice, however, standard measurements of total nitrogen (TN), such as by Kjeldahl digestion of organic compounds followed by measurement of the resulting ammonia, also include nitrogen that is not a part of the dynamic nitrogen cycle in a water body because it is contained in refractory organic matter that is merely passing through the system.

Finally, Equilibrium Concentration Enhancement (ECE) is a useful concept that can be related to spatial scale. Given a body of water of volume *V* (m^3) and relative exchange rate *E* (d^{-1}) with its surroundings, the ECE is the ratio *si/(EV).* With knowledge of the daily rate of production of NH by a farm (si), and information on scale-dependent exchange rates, a farm's ECE can be calculated on intermediate and broad scales in order to assess the significance of the farm input. On the intermediate scale, most of the ECE would typically appear as NH, whereas on the broad scale the ECE might be distributed through all components of TLN. During winter, most of the ECE could be expected to appear as DIN. The ECE concept is used by regulators in Scotland to identify the potential loading of water bodies by fish farms (Gillibrand et al., 2002).

2.2. The pelagic BEMP

This section deals only with the pelagic component of the BEMP, and draws from the most recent annual report by Aquenal (2020), which described water-column observations from March 2019 through February 2020, and presented them in the context of the time-series back to 2009.[5]

2.2.1. Sampling strategy (space and time)

According to Aquenal (2020), "*water quality sampling is undertaken monthly from May to January and fortnightly from February to April. A total of fifteen sites are included in the monitoring program; including nine sites in the D'Entrecasteaux Channel MFDP, five sites in the Huon River/Port Esperance MFDP's and one control site at Recherche Bay*". These sites are shown Figure A1. Sampling depths depended on the variable measured.

[5] Reference to a year such as 2019 is to the 12 months of observations commencing in March of that year.

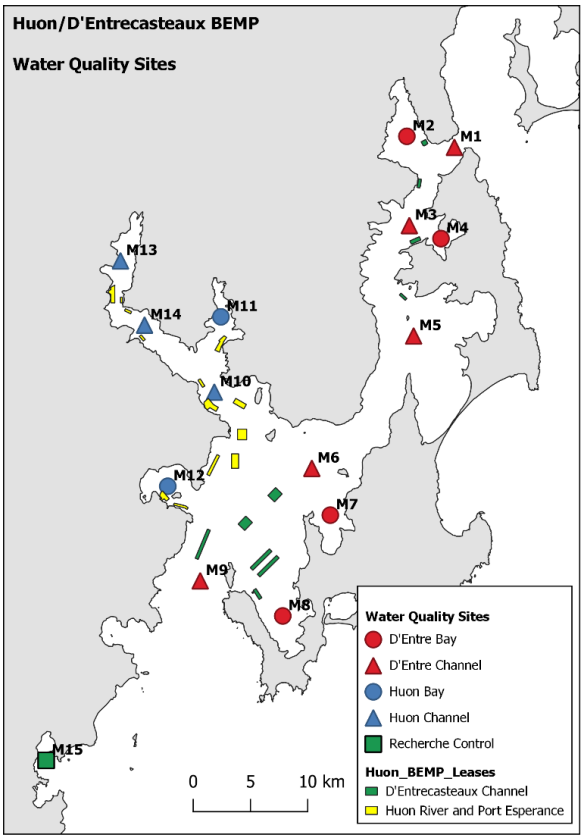

Figure A1[6]: Map showing water quality monitoring sites (M1 – M15)" (Aquenal, 2020).

2.2.2. What was measured

Water temperature, salinity and dissolved oxygen were measured by electronic probe at positions just below the sea-surface, at 5 m depth (called 'middle') and 1 m above the seabed (called 'bottom').

Water samples for nutrient analyses were taken from just below the water surface (with a "pole sampler") and by closing a Niskin bottle at 1 m above the seabed. Frozen water samples for total dissolved N, total dissolved P, and frozen filtered water samples for ammonia and nitrate were sent to Analytical Services Tasmania (AST) throughout 2009-2019, as were frozen filtered phosphate samples and chilled filtered silicate samples after June 2012. [7] Prior to this, phosphate and silicate were analysed by CSIRO.

Samples for chlorophyll and phytoplankton floristic composition were taken with a hose providing an integrated sample from 0 to 12 m depth (or to 2 m above the seabed at shallower sites). Chlorophyll concentration was measured by spectrophotometry at AST after capture of phytoplankton on GF/F filters which were then frozen. Until May 2012 phytoplankton pigments

[6] To avoid confusion, **the numbering of A. figures replicates that in the Aquenal repor**t, although the legends and additions are ours.

[7] Aquenal (2020, table 3) refers to "total N, total P … by Kjeldahl digest", in contrast with "dissolved nutrients"; but also reports that the relevant samples were "filtered at the time of collection". EPA has confirmed (through correspondence with Aquenal) that the TN samples were not filtered.

were also analysed by HPLC at CSIRO; subsequent samples have been stored (deep-frozen) in case analysis is required.

Floristic samples were analysed microscopically by AST and reported as cells/mL of each of the main taxonomic groups of micro-algae, plus abundances of potentially harmful species.

Table 2 compares the BEMP pelagic variables with those that are part of the Comprehensive Procedure in OSPAR's 'Strategy to Combat Eutrophication'.

Table 2: Comparison of OSPAR (2003) harmonised monitoring criteria and BEMP pelagic parameters (Ross & Macleod 2013). Identification of a sea-area as a 'Problem Area' requires OSPAR Convention signatory states to take action to decrease nutrient inputs. In BEMP, 'baselines' used in fixing 'trigger levels' differ between the D'Entrecasteaux Channel and the Huon Estuary.

OSPAR assessment parameters	Assessment level (for Problem Area)	BEMP parameters	Trigger level 2 (moderate risk)
Category I: degree of nutrient enrichment			
2. Winter levels of DIN and DIP	concentration >50 % above salinity related and/or region-specific background concentration	Nutrients: ammonium	Summer mean up 50% from baseline or local excesses
Category II: direct effects of nutrient enrichment			
1. Maximum and mean Chlorophyll a concentration (during growing season)	concentration > 50 % above spatial (offshore) / historical background concentrations	Chlorophyll a	Any site: annual mean +200% of baseline, or average summer mean +100%, or annual average mean +50%
2. Region/area specific phytoplankton indicator species	Elevated levels (and increased duration)	Phytoplankton blooms	% obs. > 3x median rise 100%
Category III: Indirect effects of nutrient enrichment			
1. Degree of oxygen deficiency (measured by concentration, or % saturation, of dissolved oxygen (DO)	Decreased levels (< 2 mg/l: acute toxicity; 2 - 6 mg/l: deficiency)	Absolute DO concentration	50% of channel observations ≤ 6 ppm. 50% of bay observations ≤ 5 ppm. Any 2 observations < 2 ppm
Category IV: other possible effects of nutrient enrichment			
1. Algal toxins (DSP/PSP mussel infection events) (during growing season)	Incidence (related to II.2)	Harmful Phytoplankton *G. catenatum*	# of days 7 areas are closed to shellfish harvest due to HAB >336 days*

*Note: since 2013/2014 Tasmania has used weekly monitored biotoxins in shellfish flesh as primary indicator for the occurrence of harmful algae.

2.2.3. What is done with the resulting data

Annual BEMP reports (by Aquenal pty) are cumulative, each one adding a new year of data to the time-series. For most variables, a standard format is used to show patterns of variability between

sampling sites, between months, and between years. We found this standard format helpful for finding patterns in a large data matrix. The use of box-whisker plots is a good way to present variability, but has the disadvantage that the scale of graphs is set by the most extreme values. Phytoplankton abundances were presented differently, perhaps because they related to many species.

Aquenal interpreted the observations in relation to trigger levels for regulatory action that were defined at the start of the BEMP (Thompson et al., 2008; Ross & Macleod, 2013). Threshold values for trigger level 2 are shown in Table 2.

2.2.4. Summary of findings 2009-2019

We select a few variables and aspects from the most recent BEMP report (Aquenal, 2020) to exemplify and discuss. The next few diagrams, taken from that report, present information on salinity (Figures A9a, A9e), nitrate concentrations (Figures A13a, A13c, A13e), and chlorophyll (Figures A18a, A18c, A18e). To avoid confusion, **the numbering of these A. figures replicates that in the Aquenal repor**t, although the legends are ours. The variables were chosen (by us) on the grounds that salinity indicates both freshwater influence and the potential for haline stratification, nitrate is a better 'broad' indicator than ammonia for the reasons presented in 2.1.4, and chlorophyll shows total phytoplankton biomass.

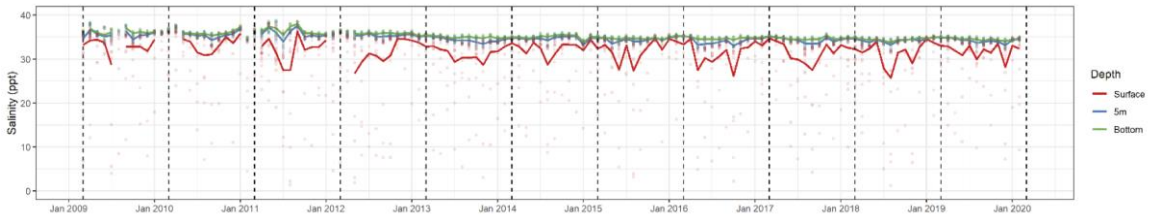

Figure A9a: Time-series of mean (over all sites) **salinities**. Mean surface salinity was always less than deeper salinities, which is indicative of persistent stratification and potential for a two-layer estuarine circulation. However, the graph is strongly influenced by data from the Huon Estuary as salinity stratification is weaker in the D'Entrecasteaux Channel.

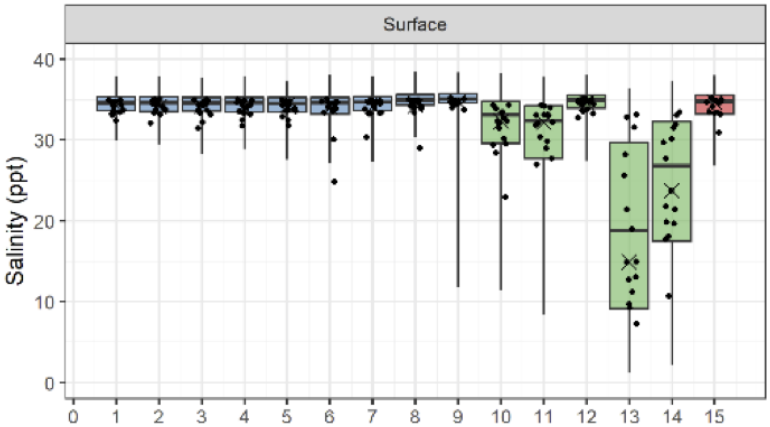

Figure A9e: Salinity statistics by site. Surface salinities in the Huon Estuary (sites 10, 11, 13, 14) were persistently lower, and more variable, than those in D'Entrecasteaux Channel. Site 15 is the 'control' site close to the mouth of the Channel.

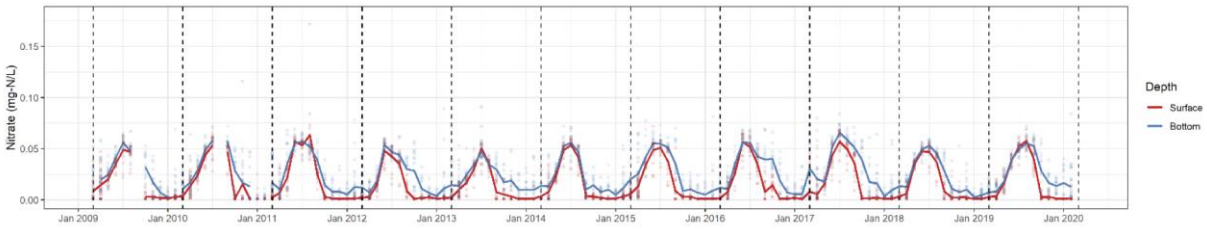

Figure A13a: time-series of mean (over all sites) **nitrate** concentrations. Surface concentrations tend to be lower than those observed near the sea-bed. Both show a strong seasonal cycle with a peak (c. 4 µM) in local Winter. A concentration of 0.14 mg N/L corresponds to 10 µM.

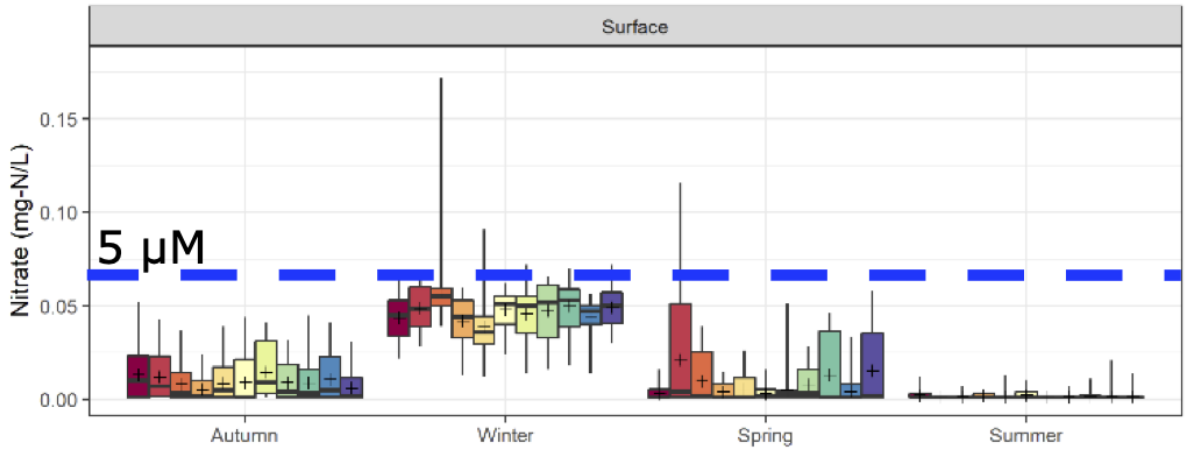

Figure A13c: Surface-layer **nitrate** statistics by season and year. Winter concentrations consistently high, summer concentrations consistently low. It is likely that variability in spring results from year-to-year variability in the timing of the spring phytoplankton bloom (either in the shelf waters or the D'Entrecasteaux Channel). (Line at 5µM added to Aquenal original.)

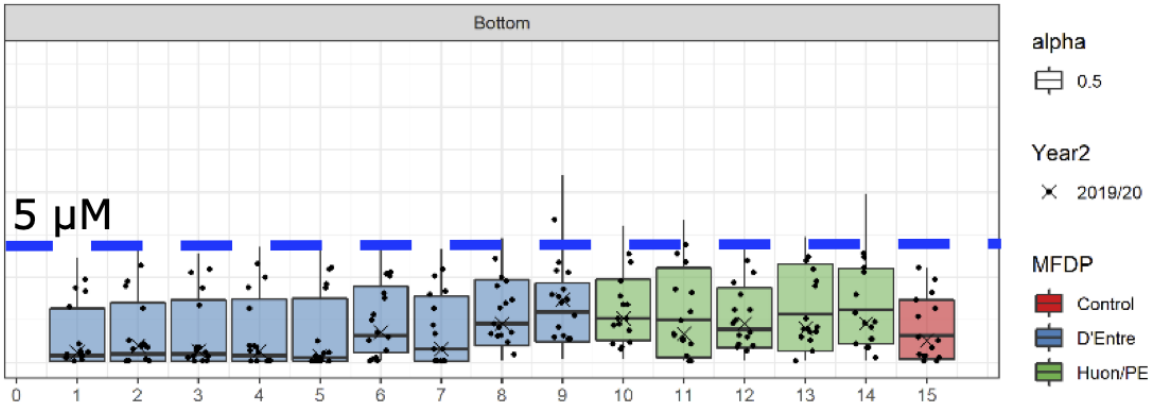

Figure A13e: Bottom-layer **nitrate** statistics by site – same vertical scale as previous diagrams. Note the differences between sites, which might partly result from site differences in sea-bed depth (and hence in the depth from which 'bottom' samples were taken).

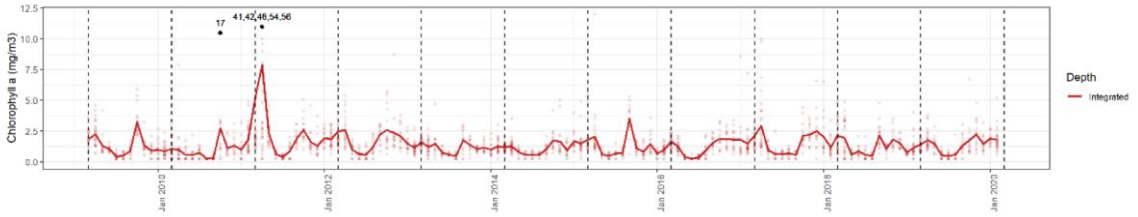

Figure A18a: Time-series of mean (over all sites) **chlorophyll** concentrations from integrating tube.

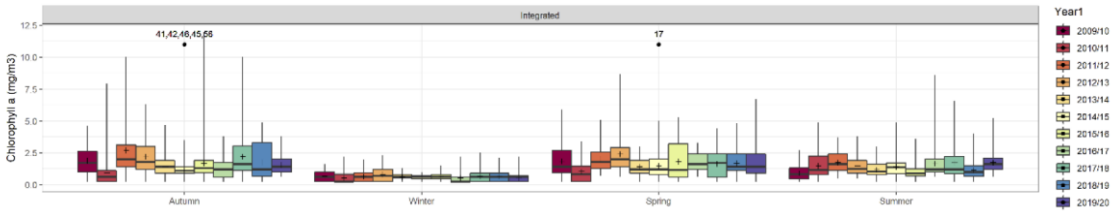

Figure A18c: Integrating-tube **chlorophyll** statistics by season and year. There is a seasonal cycle, with low winter concentrations, blooms in spring and autumn, and moderate amounts in summer, but the cycle is hard to pick out because of variability.

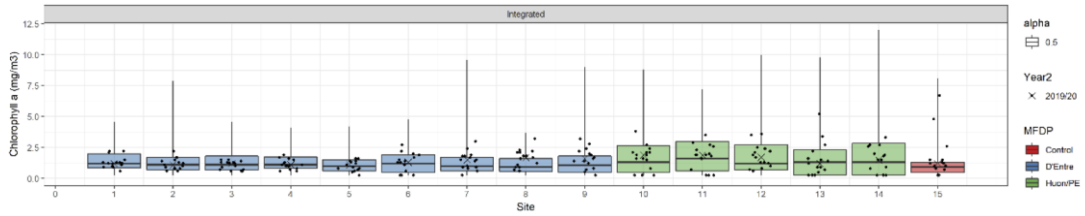

Figure A18e: Chlorophyll statistics by site. The sites seem to fall into two main groups, mainly corresponding to the colours used, which distinguish sites in the D'Entrecasteaux Channel from those in the Huon Estuary (10,11,13,14).

Ammonia concentrations were low, rarely exceeding 0.02 mg N/L or 1.5 µM, with the higher values typical of deep waters and increasing in autumn – presumably the result of sea-bed mineralisation. This variable received much attention in Aquenal (2020), because the proposed trigger levels had been exceeded for TAN in that reporting year. However, as discussed in 2.1.4, we think it less relevant to broad-scale assessment.

Concentrations of **silicate** and **phosphate** are relevant especially in relation to concentrations of nitrate and ammonia. Silicate was enhanced in the Huon estuary, presumably as a result of freshwater discharge. Phosphate ('dissolved reactive phosphorus') concentrations showed a weak seasonal cycle, but rarely fell below 0.03 g P/L (1.0 µM) even in surface waters. This would seem to confirm the assumption that nitrogen, rather than phosphorus, has been – and remains – the nutrient limiting phytoplankton growth in the HEDC.

Total nitrogen (TN) concentrations showed little seasonal or spatial pattern, but did show interannual variability. Most values ranged between about 0.14 to about 0.42 mg N/L (10 to 30 µM), indicating that there is much more TN than the maximum 5 µM that appears as DIN. Recent EPA analysis of HEDC data shows that organically-combined nitrogen averaged 95% of TN in midsummer (January 2021). Although some of this might be plankton PON and labile DON, nitrogen locked up in refractory compounds is likely to be exported from HEDC before it becomes

available to phytoplankters. **Total phosphorus** also showed little pattern, but concentrations – mainly between 0.02 and 0.05 mg P/L (0.7 to 1.6 µM) were more similar to DIP.

Information on **phytoplankton abundance** was presented (Figures A19, A22, A23) somewhat differently from that for the 'chemical variables', and the analysis is more descriptive. This may be because the microscopical data do not provide a trigger variable. [8]

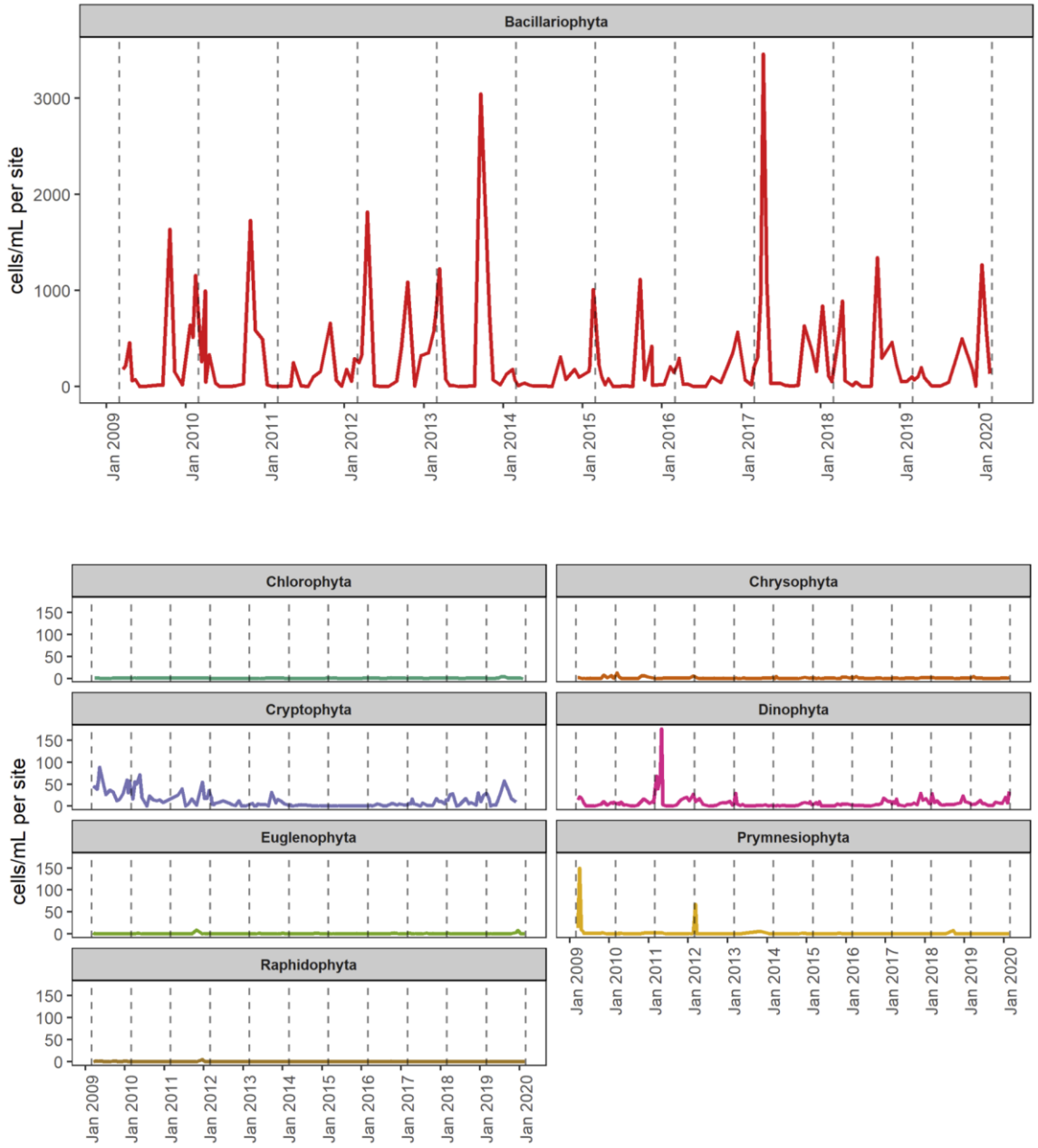

Figure A19: Mean (over all sites) abundances of **phytoplankters** (in integrated samples) during each survey event. Diatoms (Bacillariophyta) were reported as the dominant component of the phytoplankton.

[8] The phytoplankton blooms indicator is quantified using chlorophyll, not cell counts.

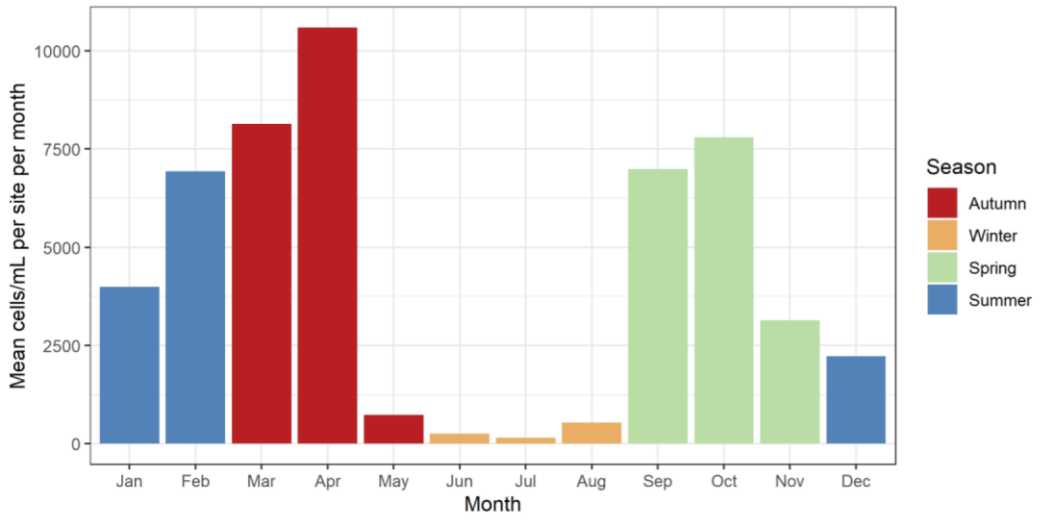

Figure A22: Seasonal pattern of **phytoplankton** abundance, data pooled over all years.

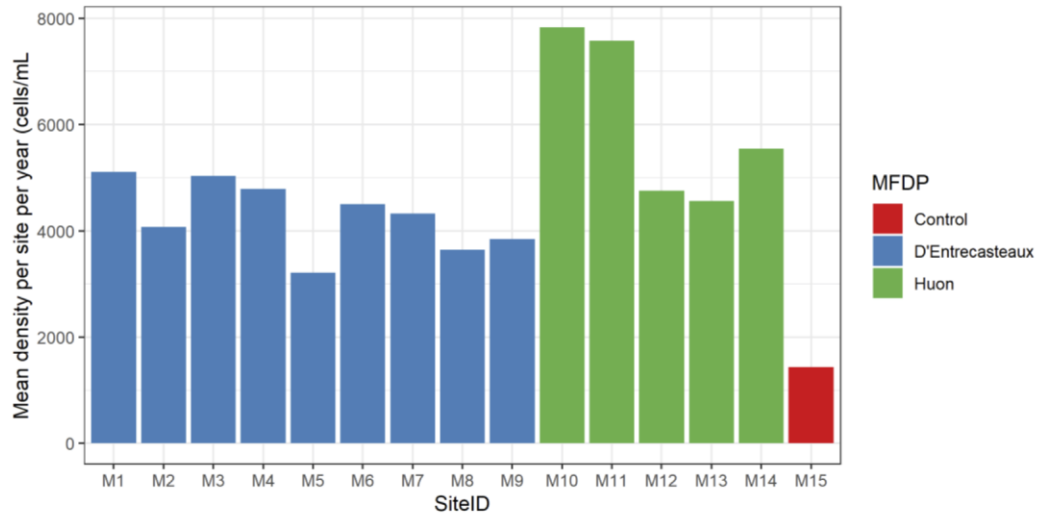

Figure A23: mean abundance of **phytoplankton** by site (all years & months).

Finally, **Dissolved oxygen (DO)** concentrations depend on the balance between production (by photosynthesis and re-aeration) and consumption (by respiration, especially that by micro-organisms). DO is often naturally depleted in deeper waters during periods in which these are isolated from atmospheric exchange. Although there are parts of the HEDC, especially in the Huon Estuary, where salinity layering restricts vertical mixing, flushing rates appear to be sufficiently high that DO rarely falls below 60% of saturation (Figure A8e).

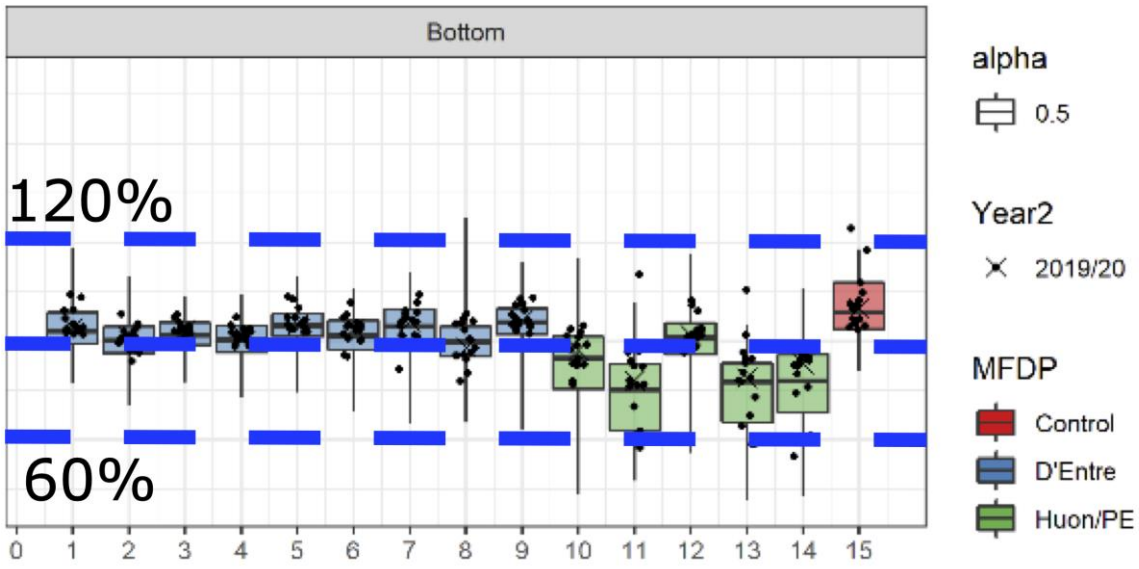

Figure **A8e**: Saturation (%) of dissolved oxygen, by sites (annotations added).

2.2.5. Conclusions drawn by Aquenal

The main conclusions drawn by Aquenal concerned comparisons between the reported values of the variables and the risk-related trigger values. Our table 3, below, summarises their findings by listing the years in which reporting statistics for the water quality variables exceeded trigger level 2.

Table 3: Summary of the years and BEMP variables and reporting statistics that exceeded trigger level 2. (* marks exceedance of trigger level 3). Only the start year is given – e.g. 2009 refers to March 2009 to February 2010. Other variables/statistics not given, nor individual sites reported. From Aquenal (2020), their tables as noted.

Variable	Statistic	D'Entrecasteaux Channel	Huon Estuary
Ammonia (tab.7)	Summer mean (bottom samples)	2019	2009, 2014, 2017, 2019*
Chlorophyll (tab.8)	Annual mean	2011*, 2012, 2016 - 2019	2011*, 2012, 2017
Chlorophyll (tab.8)	Summer mean	2011, 2012, 2019	none
Phytoplankton bloom from chlorophyll (tab.10)	Proportion of samples exceeding median	none	2011, 2012

The Aquenal (2020) report also discussed the monitoring sites (M8, M9, M10) showing the greatest exceedance, comparing the observed variables with time-series of relative N emissions from the nearest farms. It found (p.8) "*little evidence of a direct long-term causal relationship between cumulative nitrogen emissions from surrounding leases and monthly [Total Ammoniacal Nitrogen] concentrations in bottom waters at the regional scale (i.e. D'Entrecasteaux Channel or Huon Estuary) or at monitoring sites M8, M9 or M10*".

2.2.6. What the BEMP tells about the State of the Pelagic Habitat(s) in HEDC

Assessing the early years of the BEMP (2009-2011),[9] and comparing its findings with those of earlier studies, Ross & Macleod (2013) concluded that the BEMP data "*provided further evidence of the high spatial and temporal variability in nutrient concentrations and phytoplankton biomass and composition consistent with intra and inter-annual variability in hydrodynamics and marine and river influxes."* This variability remains a major feature of the state of the pelagic habitat as shown by the BEMP up to the monitoring year 2019 and no long-term trends are apparent in the diagrams taken from Aquenal (2020). Data from microscopy show dominance of the phytoplankton by diatoms during much of the year, and the nutrient data support the argument that nitrogen is the limiting nutrient, since phosphate was seldom fully depleted during the growing season. It has been suggested that the limiting nutrient might change depending on the extent to which the Eastern Australia Current or the Leeuwin Current (which differ in their nutrient content: Thompson et al., 2011) provided the main oceanic source water for the D'Entrecasteaux Channel. Graphing BEMP nutrient data against salinity in different parts of the HEDC might be informative in this respect.

The D'Entrecasteaux Channel exhibits a seasonal cycle in (available) nutrients and phytoplankton abundance and floristic composition that is not dissimilar to that observed in the shallow Scottish sea-loch Ardbhair, prior to the introduction of fish-farming. In Ardbhair the upper 90%ile nitrate concentration was 6.3 µM and the upper 90%ile chlorophyll concentration was 3.6 µg/L (Gowen et al., 1983). Typical upper 80%ile nitrate in D'Entrecasteaux Channel, and Huon Estuary was 5 µM over the BEMP period, while typical upper 80%ile chlorophyll was 2 µg/L in the D'Entrecasteaux Channel, and 3 µg/L in the Huon Estuary.[10] Interestingly, the conversion ratio for nutrient into chlorophyll according to these values is only about 0.5 µg chl per µM nitrate-N, compared with the estimate by Gowen et al. (1992) of 1.1 µg chl per µM nitrate-N across a range of sea-lochs.[11] The most likely explanation is that the population of phytoplankters that have grown by utilising DIN brought into the HEDC from the sea (or introduced from anthropogenic sources) are typically grazed down by pelagic or benthic herbivores.

Other comparisons could be made, but our impression is that the diatom-dominated phytoplankton community in HEDC is generally as expected for temperate coastal waters with low ambient N and P and enriched in Si by river discharge.

[9] Ross & Macleod (2013) refer to "*the BEMP program between March 2009 and March 2012*", that is, to the three years of monitoring commencing in March 2009, March 2010 and March 2011.

[10] In order to obtain percentile values, data are ranked in order of magnitude. The 90%ile refers to the value that is 90% of the way up the list, with the 100%ile being the top value. In the case of Gowen et al. (1983) the 90%ile values were identified from tabulated data. Aquenal (2020) used 'box-whisker' plots with the upper part of the box representing the 80%ile. However, it was necessary to eyeball the actual values, so they are approximate. No ammonium data were available for loch Ardbhair.

[11] Limnologists introduced the idea of the yield of phytoplankton chlorophyll from the nutrient (usually phosphorus) load on lakes (Vollenweider 1976, Schindler 1977). Gowen et al. (1992) built on laboratory studies of algae and observations in sea-lochs to estimate that the absorption by planktonic micro-algae of 1 µM nitrite or nitrate resulted in the formation of about 1.1 µg chlorophyll. Edwards (2001) obtained similar yields from nitrate (see also Edwards et al. (2003)) but lower yields from ammonium.

2.3. The use of models

The hydrodynamic and biogeochemical models developed by CSIRO and applied to the DHCE (Herzfeld et al., 2005; Wild-Allen et al., 2005; Volkman et al., 2009; Wild-Allen et al., 2011; Wild-Allen & Andrewartha, 2016) are a vital complement to the observational BEMP. They have provided an understanding of the hydrodynamics of the water bodies, helped design the BEMP sampling strategy, and been used for an investigation of the probable consequences of nitrogen inputs in excess of the regulatory cap. For the latter, Bell et al. (2017) studied an exceedance in 2014-2015. With the exception of ammonia/ammonium, they could find no BEMP evidence of a disturbance resulting from this exceedance, which was a comparatively small part of the nitrogen load on the HEDC. Biogeochemical simulations comparing an exceedance and a non-exceedance scenario, predicted relatively small increases in chlorophyll during the growing season. These would have been hard to detect by observation given the variability observed by the BEMP in the HEDC.

2.4. Additional analyses of BEMP data

We made some additional analyses of the BEMP chlorophyll, nitrate and ammonia/ammonium time-series, using software developed to examine seasonal patterns in Scottish sea-lochs (Tett & Wallis, 1978; Whyte et al., 2017). For this purpose, we distinguished data from three sets of locations (see map, Fig 4):[12]

- NDC (North D'Entrecasteaux Channel) : M1, M2, M3, M4, M5
- SDC (South D'Entrecasteaux Channel) : M6, M7, M8, M9
- HE (Huon Estuary) : M10, M11, M13, M14

In some cases we divided the time-series into two: the calendar years 2009-2013, and the years 2014-2019. The year-split was arbitrary. An example analysis is shown in figure 5 for SDC. The software constructed an envelope and median line for the earlier period and used chi-square to test the hypothesis of no change and with the expectation of an equal numbers of new points above and below the median. Table 4 summarises our findings from these analyses.

[12] C.f. Bell et al. (2017), who distinguished "the upper Huon estuary, the lower Huon Estuary and the D'Entrecasteaux Channel.

Table 4: summary of comparisons made using the method exemplified in figure 5 and tested with a 2x2 chi-square test (1 d.f.) with the probability of the null hypothesis (of no difference) set at 0.01 to allow for multiple comparisons. The critical chi-square is 6.6. S= surface, B = bottom.

Comparison	Chl (integrated)	NO (S)	NH (S, B)
Southern DC, comparing 2013-2019 with 2009-2012	Decrease in 2nd period	No change	Increase in 2nd period (S & B)
Northern DC, comparing 2013-2019 with 2009-2012	No change	No change	No change (S); Decrease in 2nd period (B)
Huon Estuary, comparing 2013-2019 with 2009-2012	No change	No change	Decrease in 2nd period (S); No change (B)
Comparing North DC with Southern DC, all years	More in NDC than SDC	Less in NDC than SDC	No difference (S & B)
Comparing Huon Estuary (HE) with Southern DC, all years	More in HE than SDC	More in HE than SDC	More in HE than SDC (S & B)

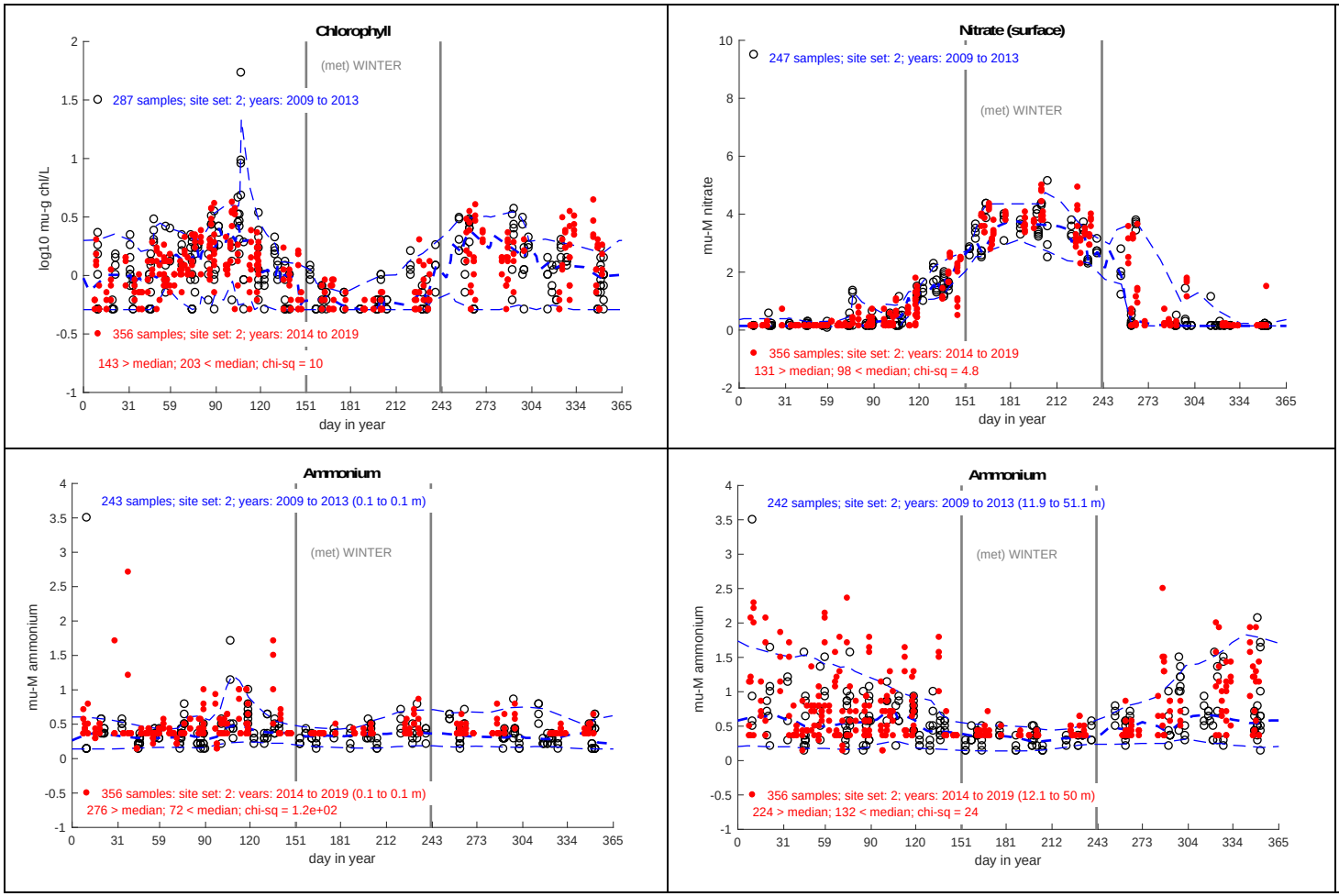

Figure 5: Seasonal cycles in years 2009-2013 and 2014-2019 in the **southern D'Entrecasteaux Channel.** Chlorophyll: integrated (0-12 m) sample (transformed $\log_{10}(x+0.01)$; nitrate: near-surface sample; ammonium: near-surface and near-bed samples. Open circles denote samples in 2009-2013, and the light dashed lines are envelopes that exclude the upper 5% and lower 5%, of points. The thick dashed line is the running median. The red points denote samples in 2014-2019. The extent of change in the seasonal cycles was measured by counting new red points above and below the blue median lines, testing for significance with Chi-square.

.

We conclude that there are significant differences between the three sub-regions, which could result from the different hydrodynamic and riverine enrichment conditions in the Huon Estuary and a tendency for phytoplankton to increase as waters flow northwards into the northern D'Entrecasteaux Channel.

Finally, we combined this method with 'Equilibrium Concentration Enhancement' (ECE) calculation, which converts estimated monthly nitrogen emissions into notional increases in DIN concentrations in the absence of algal uptake. This is a version (Greathead et al., 2006) of that used by Scottish regulators to set a cap on total farm nitrogen emission (Gillibrand et al., 2002). The resulting time-series of ECE was plotted over the 2009-2019 envelopes for nitrate and ammonium in the southern D'Entrecasteaux Channel. The diagram (Figure 6) suggests that although averaged over a year the farm inputs are comparatively small, there are months in which they are likely to be the main source of dissolved nitrogen for phytoplankton. The diagram also shows that the calculated ECE mostly exceed the ammonium median, and thus helps to confirm the argument in section 2.1.4 that ammonium is not a good broad-scale indicator of enrichment.

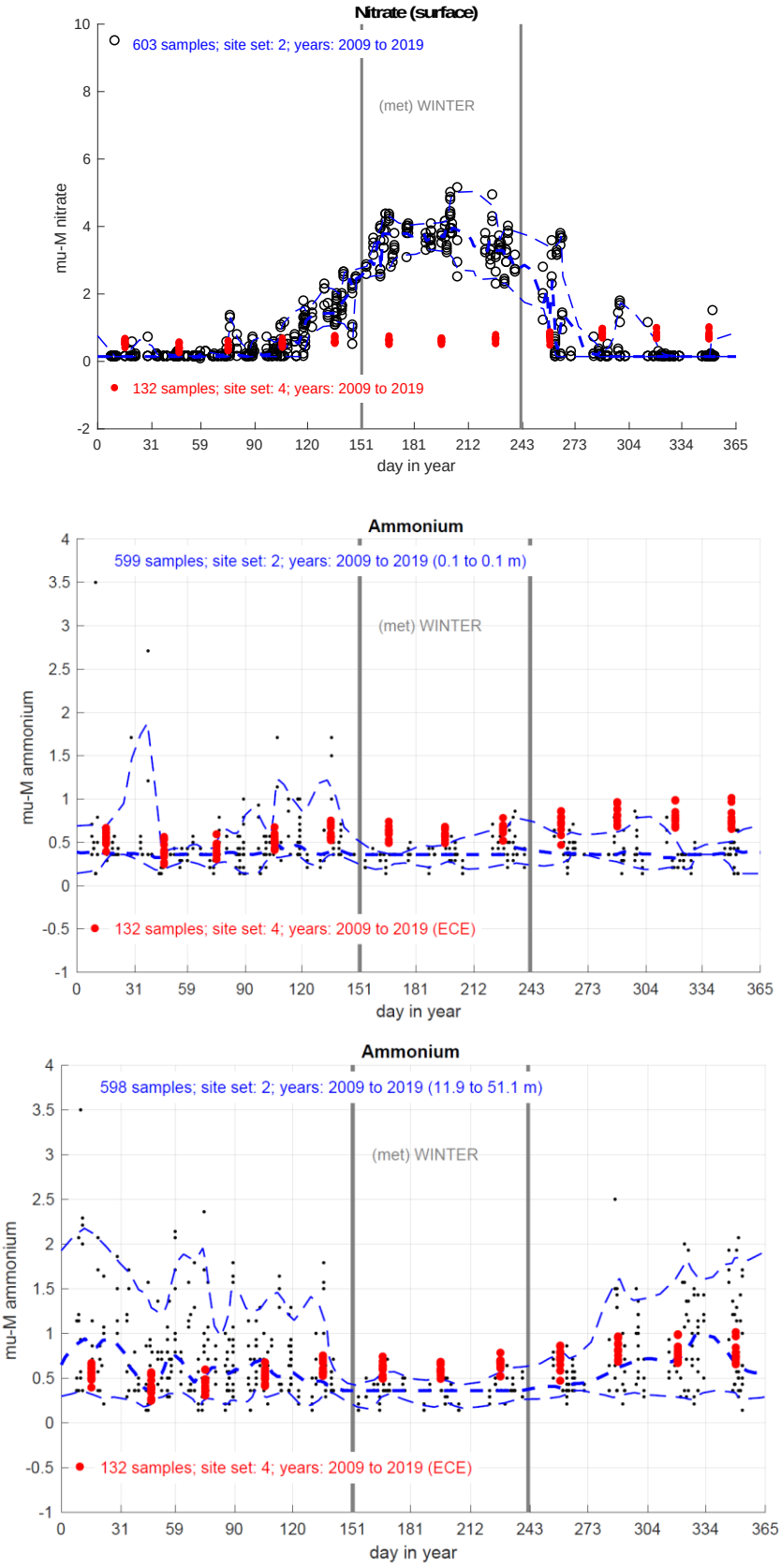

Figure 6: Nitrogen ECE values for 2009-2019 plotted (in red) over the BEMP nitrate and surface and bottom ammonia/ammonium envelopes for the southern D'Entrecasteaux Channel.

2.5. Is the BEMP fit for purpose with respect to the water column environment and the plankton?

2.5.1. Introduction

The brief for this review stated that the aim of the BEMP was "*to provide a comprehensive assessment of the ecological condition at the whole of ecosystem level in response to marine finfish farming in the same water bodies*". The review is to answer the question: "*are the monitoring frameworks within the BEMPs likely to be effective in detecting salmonid farming related broad-scale ecosystem effects within their respective MFDP areas?*"

Thomson et al. (2008) designed the BEMP strategy to monitor broad-scale effects, identifying eutrophication as the main threat to pelagic ecosystem health, and taking an approach similar to that of OSPAR in selecting key variables and setting trigger thresholds for them (as illustrated in table 2 above). Studies with models (Volkman et al, 2009) identified a set of monitoring sites within the HEDC area on the following basis (Wild-Allen et al., 2011):

"Integrated impacts of fish farm waste on labile nitrogen, phosphorus, chlorophyll and dissolved oxygen concentrations in the water column were spatially ranked to identify the most likely places to detect environmental change due to fish farming activities. Priority sites were found to be grouped in the Huon Estuary and northern part of the D'Entrecasteaux Channel consistent with the residual northward current in the region. The final monitoring program synthesized model and field understanding to ensure adequate spatial and temporal sampling of the region."

Thompson et al. 2008, (p. 5) and Volkman et al. (2009, p.161) chose sites that were representative of large areas, plus sites likely to be impacted by farms. The resulting program thus monitored against both broad ecosystem effects and effects on the intermediate scale (as defined in 2.1.4). There are, now, several reasons for rethinking the choice of sites and the logic behind the choices.

The first is simply that many data have been acquired by the BEMP, potentially enabling an improved analysis of variability over time and space within the HEDC MFDP area. The second is the arguments we have made against the emphasis on TAN as a key BEMP variable. And the third is (as we see it) the desirability of developing and tracking indicators of the State of -- i.e. the 'balance of organisms' in -- the HEDC pelagic habitats in addition to monitoring variables indicative of Pressures on that State.

We explore these points in the remainder of this section 2.5.

2.5.2. From Pressure to State

At the time that the BEMP was formulated, the approach was similar to that of OSPAR's strategy to combat eutrophication (OSPAR 2003) and the UK's 'Comprehensive Studies Task Team' model (CSTT, 1997; Painting et al. 2007): it focussed on degree of nutrient enrichment and the actual or potential direct effects on chlorophyll. Subsequently there has been a shift, stimulated by the Ecosystem Approach of the Convention on Biological Diversity of 1992 (CBD 2004), which emphasises the monitoring of ecosystem State as well as of Pressures on that State (Borja et al., 2010). Good state, in some cases reported as ecological or environmental status, could be seen in terms of:

- the absence of an 'undesirable disturbance to the balance of organisms' (Tett et al., 2007) that is part of the definition of eutrophication,
- the EU WFD's Annex V requirement for the composition and abundance of phytoplankton taxa to be consistent with undisturbed conditions;
- the EU MSFD's requirement (COM 2017) that the structure and functions of the main pelagic and benthic habitats (and their biotic communities) are not adversely affected by anthropogenic pressures.

It seems desirable that, whichever State target is chosen, more use be made of the information about the State – i.e. the floristic or faunistic composition – of the phytoplankton and macrobenthos already collected by the BEMP, as will be discussed in 2.5.8.

2.5.3. Analysis of variance

The BEMP tests the hypothesis that the regulated release of nitrogen by fish farms in the HEDC area has no detectable broad-scale ecosystem effect within this area. Detection of such an effect relies on identifying a change within the pelagic ecosystem that is (a) significant at an appropriate level of probability, and (b) more likely to result from farm nitrogen than from any other cause. A critical challenge is therefore to identify the anthropogenic component of change amidst the high spatial and temporal variability in nutrient and chlorophyll concentration. In a previous section we used a statistically robust albeit crude analysis (table 4) of the ten years of BEMP data to explore broad spatial and temporal patterns in ammonium, nitrate and chlorophyll. We now suggest the need for a more sophisticated statistical analysis – possibly a Generalised Additive Model (GAM) - of the spatial and temporal components of variability in main indicators in the HEDC system. Obvious components are:

1. the observed climatological seasonal component (which might itself be changing, long-term);
2. the observed persistent spatial components (related to site, groups of sites, or distance from an appropriate boundary condition);
3. residual variability (associated with sampling and measurement error, 'random' patchiness, short-term and interannual fluctuations from causes that include variations in weather and oceanic and riverine boundary conditions);
4. interaction terms (e.g. season and site).

Information about the spatial components will be helpful in deciding whether there is a persistent difference between the bay sites and the channel sites shown in figure A1 and in deciding on the need for BEMP purposes of all the pelagic sampling sites shown in this map. The sequence M1-M3-M5-M6-M9 was designed to pick up spatial gradients along the axis of the D'Entrecasteaux Channel, but unless such gradients are persistent and detectable from significant differences between sites, it may be sufficient to consider the Channel as consisting of just two water bodies. Similar arguments apply to the sequence M13-M14-M10 in the Huon Estuary.

Because farm annual nitrogen emissions remained much the same from 2009 through 2019, the analysis will not be able to distinguish a broad-scale farm effect on nutrients and chlorophyll. However, the biogeochemical-hydrodynamical model mentioned previously might be used for this purpose, in somewhat the same way as it was used by Bell et al. (2017) to investigate the potential

consequences of emission exceedance. In the present case the modelling task would involve subtraction of anthropogenic effects, so as to identify, for nutrients and chlorophyll:

5. the climatological seasonal component in the absence of particular anthropogenic effects (in particular, those due to nutrient release by farms)
6. the persistent spatial component in the absence of particular anthropogenic effects

Such analysis should allow refinement of the trigger levels set in 2009 for the water-quality variables[13] as well as providing reference conditions for methods assessing changes in pelagic habitat State. In addition, the analysis should lend more confidence to detection of farm-induced change in the context of the other components of variability, and thus give more credence to reports of no impact.[14]

2.5.4. Pelagic sampling strategy

Our conclusion, on the basis of the analyses shown in this report, is to suggest increasing sampling frequency whilst decreasing the number of sites. The argument for fewer sites derives from the evidence (for example figure A18e) that between-site variation in chlorophyll tends to be small compared with variability at a site. This point could be tested by the statistical analysis suggested in the previous subsection. A key argument for increased sampling frequency is that phytoplankton biomass or cell concentrations can change rapidly, doubling within a few days under favourable conditions.

If these arguments are accepted, a possible strategy would be to deploy instrumented moorings at a few sites, measuring temperature and salinity at several depths and chlorophyll by *in vivo* fluorescence at one of these depths. Depending on instrument endurance and resistance to fouling, the sites would still need visiting at regular intervals, at which time samples could be taken for nutrients and phytoplankton floristic composition. If data could be telemetered in near-real time, arrangements could perhaps be made for additional sampling of phytoplankton when blooms are observed. If the use of phytoplankton 'balance of organism' tools is adopted, there should be at least monthly sampling for phytoplankton at the mooring sites.

For the analyses summarised in table 4 we viewed the HEDC as three interconnected water-bodies: the southern D'Entrecasteaux Channel, the northern D'Entrecasteaux Channel, and the Huon Estuary. This is a division that could be tested by the results of the statistical analysis proposed above. Our suggestion is to maintain one well-sampled site in each water-body, plus an adequate site at which to determine conditions in the Tasmanian shelf sea-water entering the HEDC. Site 15 does not seem the best place to monitor such conditions, and in any case should not be called a 'control' site with the implication that it indicates how conditions would be elsewhere in the HEDC in the absence of anthropogenic inputs. A site for boundary condition monitoring should be (i) not disturbed by human activities, especially local anthropogenic nutrients, and (ii)

[13] Different baselines were provided by Thompson et al. (2008) for the Huon Estuary and the D'Entrecasteaux Channel, based on sampling in these water bodies before 2005.

[14] There is implicit in these suggestions an assumption of constant residual variability, which seems fair so long as anthropogenic enrichment is a relatively small part of the overall nutrient budget, so that the problem is detecting small perturbations against large 'noise'. The assumption would break down if ecosystem structure and function became substantially perturbed, with changes in dynamics and resilience.

typical of conditions (concentrations of nutrients, chlorophyll and phytoplankton) prior to potential growth of phytoplankton populations within the more sheltered waters of the D'Entrecasteaux Channel.

2.5.5. Scale issues and reduced nitrogen

The points made in 2.1.4 can be further developed here. The argument in that section was that 'reduced nitrogen' (NH) excreted by fish as ammonia or the ammonium ion, would be rapidly either oxidised to nitrate or assimilated by algae, so that on the broad scale, NH concentration would not be a good indicator of anthropogenic nitrogen enrichment. Indeed, on the broad scale, such enrichment might be best calculated from the nitrogen ECE and compared with observed DIN. On the intermediate scale, within which 1 or 2 days have passed since water was in contact with farmed fish, NH enriched plumes may be detected. It isn't clear, however, what added value is generated by routinely monitoring such plumes, because farmer-provided data on feed usage can be converted into NH emissions. Furthermore, it is unlikely that NH-induced changes in chlorophyll or species composition will be detectable on the intermediate scale.

This suggests that the site-related trigger levels for NH and chlorophyll, summarised in table 2, are not useful for the broad-scale. This conclusion is however dependent on nitrification rates in the HEDC, and could be tested by further modelling. Wild-Allen et al. (2010) used a relative nitrification rate of 0.1 d^{-1} in their biogeochemical model, which would be thought of as appropriate for shelf seas (e.g. Lee et al., 2002). As remarked earlier, the scientific literature reports a very wide range of rates, but it does seem as if rates in waters receiving anthropogenically enhanced ammonia inputs are closer to 1 d^{-1} (Berounsky & Nixon, 1985; McLaughlin et al., 2017).

2.5.6. Limiting nutrient(s)

The 'limiting nutrient' is the nutrient that (at any particular time and place) most constrains the formation of additional phytoplankton biomass, so that enriching this nutrient is most likely to lead to "*increased growth, primary production and biomass of algae*" (from the definition of eutrophication by Ferreira et al., 2011). It is anthropogenic addition of this nutrient that requires management, and so it is clearly important to identify it reliably. It has long been accepted that nitrogen "*is the critical limiting factor to algal growth and eutrophication in coastal marine waters*" (Ryther & Dunstan, 1971) in contrast to phosphorus limitation in freshwaters (Schindler, 1977). The BEMP's emphasis on ammonia as a trigger indicator, and the regulatory caps placed on farm nitrogen emissions, depend on a correct identification of nitrogen compounds as growth limiting.

Such identification could be made in several ways, all making use of information already collected for the BEMP. The first method was implicit when we remarked in section 2.2.4 that observed DRP concentrations rarely fell below 1 µM, implying that further uptake of P was prevented because N-limitation constrained further algal growth. The second method rests on the hypothesis that the (atomic) N:P ratio of plankton tends to 16:1 (Redfield, 1958), and the argument that the content of dissolved N and P in Winter or in source waters sets a limit to new primary production. Thus,

the Winter molar ratios of DIN:DIP of less than 2:1 in HEDC strongly suggest that biomass formation will be constrained by nitrogen.[15]

Both these methods consider effects on phytoplankton as a whole. It is also necessary to consider differential effects on components of the phytoplankton, especially concerning the need of diatoms for dissolved silica. Enrichment of nitrogen beyond a N:Si atomic ratio of 3:1 (Tett et al., 2003) could lead to Si-limitation of diatoms and thus to perturbation of the balance of organisms towards non-silica-users. The BEMP data show maximum (atomic) N:Si of at least 1 suggesting that silica limitation is not an issue. However, silica is mainly supplied in river discharge, and it would be useful to plot DIN, DRP and DSi against salinity in order to understand how N:P:Si ratios depended on river and ocean source concentrations and their mixing in the HEDC.

2.5.7. Some issues about methods of sample analysis and data presentation

1. The account of methods in Aquenal 2020 in some cases lacked sufficient details to properly assess findings. In particular there was insufficient information about the measurement of photosynthetic pigments by spectrophotometry and micro-algal abundance by microscopy. Full descriptions of methods should be made available.
2. In plotting chlorophyll data (e.g. Figure 5), it became apparent that the minimum reported chlorophyll concentration was 0.5 µg/L. The measurement method should be changed so that the limit is 0.1 µg/L or less in order reliably to describe the seasonal cycle in these water bodies. We also recommend that chlorophyll (and phytoplankton) data be log-transformed before analysis (to normalise error distributions) and before plotting (to better resolve the seasonal cycle). This would be following Butler et al. (2000), who did log-transform chlorophyll prior to statistical analysis.
3. Considerable effort has gone into analysis of components of the nitrogen cycle, including ammonia/ammonium, nitrate (perhaps including nitrite) and total nitrogen. However, only ammonia has an associated trigger level. In our view, and for the reasons already presented, it would be better to use ECE and maximum Dissolved Inorganic Nitrogen (DIN: ammonium + oxidised nitrogen) as a trigger variable on the broad-scale, since ammonium is rapidly absorbed or microbially oxidised. The method, purpose and significance of the total nitrogen measurements are unclear: they do not seem likely to be sensitive to nutrient enrichment.

2.5.8. A more holistic approach to monitoring (pelagic) ecosystem State

A more holistic approach to monitoring and reporting the State of the pelagic habitats in the HEDC would involve making more use of the phytoplankton data and a reframing of the information acquired during the BEMP. The HEDC is a system with lateral boundary conditions at the head of the Huon estuary and where the D'Entrecasteaux Channel exchanges with Tasmanian continental shelf waters. The ecosystem consists of populations of mobile animals (marine vertebrates being of particular interest), several 'pelagic habitats' containing the drifting organisms of the plankton, and a number of important benthic habitats. Although an overall assessment of ecosystem State

[15] Values were eyeballed from Aquenal (2020), giving the upper 80%ile during months of highest DRP as 0.15 mg/L or 5 µM (Aquenal report fig 14), for nitrate 0.07 mg/L or 5 µM (fig. 13), and for ammonia/ium 0.02 mg/L or 1.4 µM, giving DIN as up to 7 µM and a DIN:DRP molar ratio far below 16:1. (The phosphate values are surprisingly high; expectation for temperate coastal seawater is maximum DIP around 1 µM.)

should consider the condition of all these components, we think that impacts of anthropogenic nutrient and organic inputs are most likely to be apparent in the pelagic and benthic habitats and the biotic communities found there.

In the BEMP analysis of water-column data, the HEDC sites are divided into two main groups: those in the D'Entrecasteaux Channel, and those in the Huon Estuary. Our own analysis suggests distinguishing between the northern and southern D'Entrecasteaux Channel, so making three distinct pelagic habitats. The key pelagic habitat State data are those relating to phytoplankton floristic composition, already collected by the BEMP. There are several ways to analyse and present phytoplankton data that are more likely to detect change. We suggest use of a 'balance of organisms' indicator that takes account of the seasonal cycle and groups ecologically-related species as 'lifeforms'.

Suitable indicators include the `Seasonal Succession Multi-Metric' in the UK Coastal Waters Phytoplankton Tool (Devlin et al, 2007, 2009) developed for the WFD (Devlin et al., 2014) and the Plankton Index, originally developed for detecting 'undesirable disturbance in the context of eutrophication' (Tett et al., 2007; Tett et al., 2008) and used for tracking change in semi-enclosed coastal water bodies (Gowen et al., 2015; Lei et al. 2018) and as part of the UK's pelagic habitats monitoring strategy for the MSFD (now, post-Brexit the UK Marine Strategy) (McQuatters-Gollop et al., 2019).

2.5.9. Reference conditions

Trigger levels for some BEMP variables – e.g. chlorophyll – already distinguish the D'Entrecasteaux Channel from the Huon Estuary. We suggest the need to identify seasonally-varying reference conditions for all trigger variables and for the State indicators in each habitat. Such reference conditions might need to be dynamic, if boundary conditions alter due to (for example) climate change.

In the case of nutrients and chlorophyll variables, modelling could be used to subtract anthropogenic effects from BEMP observations. Both the above-mentioned phytoplankton 'balance of organisms' indicators explicitly require reference condition data, because they report deviations from these conditions. The reference conditions could be those of an undisturbed water body of the same hydrodynamic type (if following the WFD approach) or could be an arbitrary period within the existing time-series (if following the MSFD approach of tracking change relative to Pressure change).

3. BENTHOS AND SEDIMENTS

3.1. Mechanisms of interaction between marine cage fish farms and the benthic environment

Interactions between fish farms and the environment at the local scale are quite well understood and modelled (e.g. Keeley et al., 2013a, b; 2014; 2015). Particulate organic material (POM) from fish farms is comprised mostly of fish faeces, waste feed (including feed dust from feed blowers), fouling organisms (unintentionally detached or otherwise) and fish scales. In areas of moderate to high current flow, POM from fish farms can extend for some distance either directly through primary settlement or indirectly via resuspension of POM previously deposited near the cages.

POM that settles on the seabed is consumed by microorganisms increasing oxygen consumption. This oxygen deficit stimulates anaerobic processes including sulphate reduction and methanogenesis. Sulphate reduction produces sulphide which is toxic to metazoan life at quite low concentrations, although some benthic invertebrates have some tolerance. The reduction in oxygen and the increase in hydrogen sulphide in sediments enriched with organic waste has quite predictable effects on the animals that live in and on the seabed (Pearson & Black, 2001). Typically, if the number of species is reduced (biodiversity) and the animals that flourish are small, specialised opportunists may become present in great numbers. If the rate of organic material supply is too great then even these opportunists are excluded and the sediments can produce gas bubbles containing hydrogen sulphide, carbon dioxide and methane.

In most regulatory regimes, local benthic impacts are the key tool for determining marine cage farm environmental performance as changes in the benthic community structure are quite sensitive to the rate of organic matter supply and relatively easy to sample and analyse. Models are available that attempt to predict the response of the benthos to the scale of the fish farm in the context of the ambient environmental conditions, particularly currents and depth (Cromey et al., 2002; 2012).

In the early days of the industry, where equipment frailty required occupation of quiescent, sheltered, shallow sites, benthic effects were typically constrained to the immediate area of the cages (Brown et al., 1987). There is much evidence, in the modern industry often situated in more open, deeper and dispersive settings, that benthic effects can be considerably more widespread, depending on local circumstances, particularly at high flow rates (Keeley et al., 2013b). A few examples follow. In a modelling study, Sara et al. (2006) could detect the stable isotope signature of particulate organic matter from fish farms up to 1000 m from fish farms around Sicily. Kutti et al. (2007 a, b) found that the large-scale benthic effect at a deep Norwegian farm was restricted to 250 m from the farm but that fish farm waste could be detected up to 900 m from the cages in C-13 isotope ratios and fatty acid analysis. Bannister et al. (2016) working at the same site predicted that 75% of organic effluents are dispersed to near-field sites (< 500 m from the release point), while a small proportion of particulate organic effluents (up to 2.7%) are dispersed to far-field sites (>2 km). Diaz-Almela et al. (2008) found that seagrass mortality scaled with sedimentation rate leading to the exclusion of *Posidonia oceanica* from within 100 m from fish farms. Benthic impacts from relatively shallow dispersive Scottish fish farms at between 50 and 100 m is considered normal (unpublished SAMS data).

Nevertheless, it is fair to say that benthic impact is generally localised around the farm and, while some material may be exported for long distances, any benthic effects are generally difficult to detect at the wider scale owing to dispersive processes diluting the material. One exception to this is where maerl[16] beds are present that can trap particles (Hall-Spencer et al. 2006). Volkman et al. (2009, p.161) concluded that, as only 4% of 88 benthic surveys in the Huon Estuary / D'Entrecasteaux Channel had found any benthic effect outside the lease areas, it was unlikely that the Industry was having an effect on the benthos outside these areas more generally.

A secondary mechanism of impact is plausible: unless limited by another factor (e.g. light), nutrients from the marine cage farming could cause an increase in local primary production that is retained within the basin of origin rather than being exported. In such cases an effect on the seabed may be observable from the sedimentation of senescent phytoplankton or the faecal pellets of grazing zooplankton. There are relatively few examples in the literature where such phenomena (eutrophication) have been attributed to marine cage fish farming (reviewed in Price et al., 2015) and any effect will likely be related to the proportion of primary production attributable to fish farming nutrients compared to nutrients from other sources, as well as a range of other factors e.g. basin exchange rate (see section 2 on water column effects).

3.2. The BEMP

3.2.1. Monitoring Station selection

Water-column stations were established on the basis of modelling predictions. However, as the model used to determine the water-column stations (on the basis of predicted nutrients, chlorophyll and reduced dissolved oxygen caused by fish farms) had low sediment transport skill and so could not be used to optimise the position of benthic stations, the water-column stations were also used as the benthic/sediment stations by default (Thompson et al., 2008). In fact, the water-column and benthic/sediment stations are not all co-located as the benthic stations were in some cases moved somewhat to align with previously used benthic reference stations to allow continuity of existing time series (Aquenal, 2020, Figure 1, although it appears that this continuity of data has not been reported).

3.2.2. Benthos and sediments: sampling and analysis

Triplicate macrobenthic samples are collected using van Veen grab, from a total of 15 stations (Aquenal 2020, Table 2) fixed in buffered formalin and sieved at 1 mm before preservation in 70% alcohol in the Autumn (typically in April). Identification of benthic fauna to family level is performed every 4 years with samples from intervening years archived. Identification was carried out in 2009, 2013 and 2017, and will be undertaken again in 2021.

Triplicate sediment cores (50 mm i.d.) are collected at each of the same stations at the same time as benthos sampling and assessed for length, colour, visible animals and plants, gas vesicles and smell. Core samples are also archived for particle size and stable isotope analysis.

[16] https://en.wikipedia.org/wiki/Maerl : Maerl is a collective name for non-geniculate coralline red algae.

Redox potential (-3 cm) is measured in each core by probe. Sulphide is measured in sediment taken from a side port of each core using a silver / sulphide electrode and a calibration curve determined from sulphide standards.

Particle size and stable isotope analysis of sediments was carried out in 2009, 2013 and 2017 and will be carried out next in 2021.

3.2.3. Macrobenthos and sediments results

Analysis of benthos from sampling undertaken in 2009, 2013 and 2017 revealed no major shifts in community composition (Aquenal, 2018). Samples were identified to family level and assessed using univariate metrics (e.g. abundance and number of species), using traditional K-dominance and Multi-Dimensional Scaling plots (MDS) using PRIMER, a statistical package developed by the UK Plymouth Marine Laboratory. Visual assessment of cores from 2019 did not reveal any major changes since monitoring began in 2009 (Aquenal, 2020). Redox potential (-3 cm) has remained positive and relatively stable across the whole sampling period (Aquenal, 2020, Fig 2) and sulphide samples were well below 100 µM, almost always < 10 µM (Aquenal, 2020, Fig 4).

Particle size analysis results reflected the degree of exposure to waves and currents and have varied somewhat over time (Aquenal, 2020, Figure 9). C/N ratios and stable isotope results were similar between sampling events. Stable isotope results did not show any broad scale effect attributable to fish farming (Aquenal, 2017).

3.2.4. Reefs and macrophytobenthos

Reef communities and the macrophytobenthos are not included in the BEMP at present although this was envisaged in the early genesis of the BEMP (Thompson, 2008). There have, however, been studies aimed at trying to better understand any potential interaction between the salmon farming industry and such habitats.

> Oh (2009) *"investigated the effect of salmon farms on macroalgae in* [the D'Entrecasteaux Channel]*. Data on the macroalgal community were collected from two depths at 44 sites of varying distance from twelve active fish farm leases. This included reference sites at distances of 5 km or more. The sites were widely distributed throughout the study area, and varied in their exposure to wave action. The macroalgal community composition differed significantly between sites at 100 m from fish farms and sites at 5 km or more. Sites at 400 m varied in their response to farms, with some sites showing characteristics similar to 100 m sites. Impacts varied between swell exposed sites and sites only subjected to wind-generated waves. Chaetomorpha spp. and Ulva spp. were abundant near fish farms at exposed sites, whereas the abundance of filamentous green algae increased at sites near fish farms in sheltered sites. The percentage cover of indicator groups such as epiphytes and opportunistic algae in total provided the best indicators of fish farm impacts on a broad scale. The percent cover of canopy forming perennial algae did not decrease near fish farms indicating that their growth and recruitment has not been greatly affected by high levels of sedimentation from fish farms or prolonged fouling by opportunistic algal epiphytes to the present…"*

Oh et al. (2015) assessed reef communities at 4 fixed distances (100 m, 400 m, 1 km and 5 km) at 44 sites and found that sites at 100 m distance differed significantly from 5 km distant sites with the other 2 distances being intermediate in effect. They suggested that their results showed that nutrients from fish farms affect reef communities at variable distances at scales of hundreds of

meters but rarely at kilometres and that the nutrients from farms might be assessed better using seaweeds which accumulate nutrients over time rather than from spot measurements of the nutrients themselves.

Valentine et al. (2016) conducted a time series analysis of macroalgal community structure data from a dataset of Tasmanian Marine Protected Areas (MPAs) (1992-2015) including sites both close to and far removed from fish farms. They found that there were no clear temporal trends in the data and no evidence of increases in nutrient indicator species over time, although one of the sites at Tinderbox, close to a fish farm, showed a big increase in *Caulerpa* spp. abundance. *Caulerpa* spp. are not thought to be indicators of nutrient enrichment.

Recreating an earlier unpublished study on intertidal algal community structure carried out in 2002/3 (Crawford et al., 2006), Crawford and Harwin (2018), sampling in 2015/16, sought to assess changes in the intervening 12 years during which the industry had increased its production considerably. Both studies focused on *Ulva* spp. and *Hormosira banksii*. As in the earlier study, they found no clear patterns of abundance in relation to distance from fish farms in either species. However, the abundance of *H. banksii* was significantly lower in 2015/16 than 2002/3 whereas the proportion of *Ulva* spp. had increased. They concluded that factors other than fish farms were responsible for these changes as they were consistently found regardless of proximity to fish farms.

The possibility that fish farming causes sedimentation on reefs in the region was examined by Macleod et al. (2016). Their study demonstrated that "dust" collected from macroalgae was not salmon food or faeces. Sedimentation rates at reef sites were not related to distance from fish farms nor were the stable isotope and fatty acid signatures. However, it was acknowledged that neither stable isotopes nor fatty acids (using terrestrial components of the fish feed as tracers) were particularly good indicators given the volume of terrestrial inputs into the system.

Epiphyte coverage of macroalgae can be an indicator of nutrient enrichment and has been shown to be linked with salmon farming (Oh et al. 2015; Haugland et al., 2021). The Tasmanian EPA has committed to undertake strategic monitoring of the volume and extent of epiphytic algae growth on shallow reef and seagrass habitats across the southeast of Tasmania. Monitoring will be undertaken of suitable habitat from Cockle Creek to north of Maria Island. The monitoring aims to improve the understanding of fluxes in epiphytic algal growth in response to natural coastal processes as well as anthropogenic interactions, primarily salmon farming activities. Monitoring by the Water Section of the EPA commenced in late January 2021 to provide a snapshot of conditions epiphytic algal growth during late summer 2021. (EPA pers. comm.)

An initial 100 sites have been selected covering:

- D'Entrecasteaux Channel (mid and lower)
- South Port
- Port Esperence
- Frederick Henry and Norfolk Bays
- Marion Bay area
- Mercury Passage

The Institute for Marine and Antarctic Studies (IMAS) has been commissioned by the EPA to undertake snapshot surveys throughout the northern D'Entrecasteaux Channel area. IMAS have also undertaken to investigate epiphytic algal growth throughout Port Arthur and Nubeena Bay though a range of research projects.

IMAS conducted assessments of epiphyte coverage on reefs and seagrass beds in the northern D'Entrecasteaux Channel in November 2020 and again in December 2020 (White et al., 2021). ROV snapshots of distance gradients from three fish farms were conducted together with several broadscale sites, including sites on the north coast of Bruny Island, and two stations outside the channel – a total of 33 stations. Sites within the North Channel showed substantial epiphyte cover in the North Channel sites (average score 3, see table 5), whereas sites outside the North Channel had low or very low epiphyte coverage. The authors conclude that:

These results indicate that epiphytic algae cover is still high throughout the North Channel, however a moderate decrease has occurred since the previous survey across most sites. Further evidence for a localised, but variable response in epiphytic algae on reef and seagrass adjacent to salmon leases was observed, through both elevated epiphytic algae at stocked leases Sheppards and Tinderbox, as well as a reduction in algae at Simmonds following a substantial fallowing period. To better understand these general trends, IMAS will repeat the ROV surveys in the North Channel on a semi-regular basis throughout 2021.

Table 5: Description of the scoring system used to assess epiphytic growth (White et al., 2021; Table 3.).

Score	Description
0	No epiphytic growth present
1	Very low epiphytic growth, virtually clean plant.
2	Low, minimal epiphytic growth.
3	Medium, obvious epiphytic growth.
4	High, most of plant covered.
5	Very high, plant completely covered.

Recent unpublished work by IMAS has trialled the use of Rapid Visual Assessment (RVA) as a complement to more traditional biodiversity assessments of reef biodiversity (Edgar-Barret). RVA involves the scoring of functional parameters (e.g. red encrusting algal cover) of the reef by diver.

"At present the method shows great promise as a simple and dependable tool for monitoring organic enrichment on temperate reefs. While the RVA technique can be used with confidence to detect change in reef function, it needs reliable baseline data for comparison at suitable spatial and temporal scales, if it is to be used to assist in the determination of attribution or source of impact."

This technique will be of great utility in future monitoring of reefs in the HEDC BEMP.

3.3. Is the BEMP fit for purpose with respect to sediments and benthos?

We are assessing this question: "*Are the monitoring frameworks within the BEMPs likely to be effective in detecting salmonid farming related broad-scale ecosystem effects within their respective MFDP areas?*"

3.3.1. Station number and location

Benthic stations were not selected to maximise the prospect of observing likely subtle effects. Where they exist, sediment and benthic effects might be most likely to occur in areas where sediments naturally accumulate, for example in topological depressions with fine sediments. Indeed this was also noted by Thompson et al. (2008, Appendix 6): "These key sites should include sites that may be vulnerable to organic enrichment either as a result of their location (i.e. deep holes or other depositional areas close to farming activities)…"

The LISTmap[17] (Land Information System Tasmania) has sediment type information (sourced from Barrett et al., 2001, determined from processed echo-sounding) and we determined the LISTmap sediment type for all the benthic stations for which there are data (some of the Huon Estuary does not have sediment data and there is nothing below 40 m in the south Channel). We also looked for nearby depressions or apparently softer sediments to see whether such could have been chosen without much extra effort. However, the LIST sediment type information is not in some cases consistent with the sediment particle size information at the BEMP sites (Ross & MacLeod 2013, Fig 3.7; Aquenal, 2018). The particle size information (%fines, <63 µm) from Aquenal (2018, taken from Figure 9) is given for each station in Table 6. The data used are from the 2013 survey as they were generally finer than in 2017.

[17] LISTmap - Land Information System Tasmania (thelist.tas.gov.au)

Table 6: BEMP Benthic/Sediment Stations, position, depth and % fines. Proportions of fines (< 63 µm) below 50% are in red type.

	Aquenal 2020[#]				
	Name	**E**	**N**	**depth***	**%fines[#]**
B1	Northern Boundary	527388	5232358	14	32
B2	Northwest Bay	524236	5233512	24	72
B3	Sheppards Point	524089	5227962	22	37
B4	Roberts Point	525224	5224328	14	25
B5	Soldiers Point	522337	5219690	25	45
B6	Green Island	524125	5215637	13	36
B7 (rev)	Zuidpool	511188	5202954	[$]40	79
B8	Great Taylors Bay	512028	5194350	42	74
B9	Lippies Point	504495	5195745	46	29
B10	Garden Island	507993	5210571	32	76
B11	Deep Bay	507095	5213795	20.9	75
B12	Dover	502357	5202639	30	78
B13	Pillings Bay	498168	5220383	11.3	75
B14	Brabazon Point	500172	5217258	15	67
B15	Recherche Bay	492064	5178637	7	21

*Ross, D. J. & Macleod, C. K. (2013). Evaluation of Broadscale Environmental Monitoring Program (BEMP) data from 2009-2012. IMAS Technical Report 140pp

[#]Aquenal (2018) Broadscale Environmental Monitoring Program – D'Entrecasteaux Channel and Huon Marine Farming Development Plan Sites – Annual Report 2017/2018, Fig 9, 2013 data.

[$]LISTmap

Station B15 in Recherche Bay is described as a "control" station. Firstly, the word control is misleading as it implies an experiment: experimental controls imply that "all other things are equal" except the variable being assessed. This is not applicable in the present case or indeed to monitoring in the marine environment in general. More importantly, B15 is located in much shallower water than any other station (7 m; Ross & Macleod, 2013) with a sandy substratum (21% fines, Table 6), certainly being more influenced by wind-wave action than any other station, making it highly unsuitable as a reference. Station B15 is of such limited value as to warrant deletion.

Can we locate stations in places that would be better at detecting any effects from fish farming? The bathymetry given in LISTmap reveals several depressions that might offer good potential. The hydrodynamic model that has been constructed for the area is likely to be able to provide some helpful information on other potentially accumulating areas. The best accumulating sites would have to be determined by a field programme. Long cores at these sites could be dated (Pb-210 and bomb Cs-137) to determine sediment accumulation rate and used to identify any biogeochemical marker which might be associated with fish farming.

A field survey of potential alternative positions in more accumulating locations should be undertaken. On the face of it there is a case for moving Station B3 to a nearby depression if that proves suitably accumulating.

3.3.2. Sampling frequency

Sampling is carried out annually in the Autumn with benthic samples, particle size, C/N and stable isotope samples being analysed only every 4th year and samples retain for intervening years. Visual assessments, redox and sulphide analyses are performed annually. Given that the benthic analysis carried out to date does not give cause for concern, the 4-year interval between macrobenthic analyses is reasonable provided that any worrisome changes in the sediment measurements immediately trigger appropriate analyses of some or all of the samples archived from the intervening years.

3.3.3. Sampling parameters and replication

The analyses carried out are all unexceptionable. We would recommend that consideration be given to molecular taxonomic methods for benthic assessment. These are cost effective and give very rapid responses compared with traditional manual identification of organisms. Diversity indices derived from environmental DNA samples are consistent with traditional benthic indices measured from the same samples (Lejzerowicz et al., 2015; Aylagas et al., 2018; Pearman et al., 2020; Steyaert et al., 2020).

The stable isotope work is interesting and should be continued. However, the reference values from fish feed in the BEMP report of the 2017 sampling (Aquenal, 2018) cite data from 2000. Since 2000 there has been a considerable increase in the proportion of terrestrial agricultural components in fish diets so it would make sense to compare the environmental sample with values taken from fish food at the time of sampling. If a large amount of terrestrial material is being included to the feed in Tasmania, then further consideration should be given as to the utility of this technique.

From preserved samples, it might be worth analysing some of the C/N ratios and stable isotopes for example looking at annual trends within stations “downstream” of large fish farms. Compound specific stable isotopes (Isotope ratio Gas chromatography Mass spectrometry IR-GCMS) are the only realistic way of attributing cause and effect with any certainty from organic components – certain metals may also be useful (e.g. Cu, Zn, Cd: Dean et al. 2007).

The replication rate (triplicate) of the sampling is reasonable given that these are time-series data rather than a one off Before-After-Control-Impact (BACI) study.

3.3.4. Data analysis and presentation

The survey report authors make use of Multidimensional Scaling which is good at visualising similarity between stations and K-dominance curves which visualise relative differences in community composition. They do not make use of the numerical biodiversity or ecological group balance indexes (AMBI, ITI, Shannon-Wiener, etc.) typically used in benthic survey analysis (Borja et al. 2009; or ES developed in New Zealand by Keeley et al. 2012) which can indicate enrichment status. Some of these indices work well at family level (e.g. BQI: Karakassis et al. 2013). We recommend that the data analysis includes biodiversity and group balance indices that tolerate

family level data – this should not be much extra effort and could easily be computed for previous analyses to look at trends.

Data presentation is good although station names seem to have changed somewhat over the years (e.g. Green Island B5 in Ross & Macleod (2013) becomes Green Island B6 in Aquenal (2020)).

4. CONCLUSION

4.1. Introduction

This review aimed to address, in respect of the Huon Estuary and D'Entrecasteaux Channel MFDP, the question: "*are the monitoring frameworks within the BEMPs likely to be effective in detecting salmonid farming related broad-scale ecosystem effects within their respective MFDP areas?*"

Our answer is, broadly, yes. However, there are opportunities to modernise the HEDC program in respect of data collection and the subsequent (numerical) analyses of those data. In addition, we suggest more emphasis on the evaluation of habitat and ecosystem State whilst remaining alert to trigger variable exceedances.

4.2. General

Although the main aim of the HEDC BEMP was in 2009, and remains in 2021, the detection of salmonid-farming related, broad-scale ecosystem effects, it has provided a decade-long time-series of water and sediment quality variables that, taken together with the findings of earlier research and modelling studies, allows the tracking of potential change in ecosystem State in response to exogenous Pressures such as climate change in addition to responses to the endogenous and locally manageable Pressure of fish-farming. Distinguishing between endogenous and exogenous Pressures reduces the risk that fish-farming will be blamed for changes for which it is not responsible.

In addition to detailed and technical recommendations, that are essentially to do with the answers to the questions of what, where, and when, to sample, we have one more general recommendation. It is as much concerned with the conceptual framework that influences how BEMP data are used, as with the practical matters of how those data are obtained. Current management relies on trigger levels established by Thompson et al. (2008) for a small set of water quality variables, especially concentrations of ammonia, chlorophyll and dissolved oxygen.

In line with modern practice in monitoring the condition of marine ecosystems, we are recommending that more attention is paid to the State of the main pelagic and benthic habitats that, together with populations of mobile species such as fish, marine mammals and sea-birds, make up the ecosystem of the HEDC. We do not envisage the BEMP including the mobile populations, because we think that broad ecosystem effects, if any, will first be detectable and explicable at the habitat level.

Currently, the BEMP includes only the soft-sediment habitats and the upper-water-column pelagic habitats, which are the most extensive habitats within the HEDC system and the most important for its functioning. However, Thompson et al. (2008) also recommended that "Seagrasses and other macrophytes" should also be monitored as part of the BEMP, and we underline this recommendation and urge that current monitoring of sea-grass and hard-bottom benthic habitats/communities, described above (3.2.4) and currently commission by EPA to obtain more information on epiphytic growth due to public concern about increased 'Nuisance' algae, should be included within the HEDC BEMP.

Although much effort has been directed in the BEMP at getting information about the floristic composition of the phytoplankton and the faunistic composition of soft-sediment benthos, little use has so far been made of this information. We recommend adoption of the habitat 'balance of organisms' indicators, mentioned in preceding sections, as tools to simplify reporting on the condition of these communities and to better identify changes in ecosystem State. If adequately unperturbed reference conditions can be identified for the HEDC habitats, a strategy similar to that of the Water Framework Directive can be used as a trigger for regulatory action. If reference conditions cannot be established, changes in State indicators that relate to changes in endogenous Pressures can be used as triggers. Modelling as well as statistical studies are useful in establishing causal links, as exemplified by Bell et al. (2017).

Finally, we suggest that a 'report card' system summarising the current state of each main pelagic and benthic habitat, could be used to inform the public of the State of the HEDC ecosystem. Simple colour icons, sometimes called 'traffic-light indicators' can be misinterpreted. Nevertheless, the UK finds them useful for reporting the components of environmental condition under the UK Marine Strategy. combining a green, orange or red icon with an arrow showing direction of change and a sentence of text. An alternative is the Water Framework's system of colour coding water bodies on maps, to show overall quality status.

4.3. Water column and pelagic habitats

4.3.1. Data presentation and analysis

1. Rethink the use and presentation of data for the components of the Nitrogen system; use TAN (NH) as local indicator and DIN (NH+NO) as the main broad-scale variable; total N as presently measured seems unlikely to detect broad-scale farm effects.
2. Routinely plot dissolved nutrient concentrations, and their molar ratios, against salinity, in order to substantiate assumption of nitrogen limitation throughout the HEDC.
3. Use logarithmic transformation for chlorophyll concentration and phytoplankton cell abundances
4. Carry out statistical analysis of existing BEMP data to better understand sources of variability and potential to detect change
5. Use a 'balance of organisms' indicator to track year-to-year changes in phytoplankton floristic composition.

4.3.2. Sampling strategy

6. Use results of the statistical analysis to evaluate current sampling strategy, and to consider reducing number of sites, perhaps to one in each of Huon Estuary, northern D'Entrecasteaux Channel, southern D'Entrecasteaux Channel, and an open-sea boundary condition;
7. Consider using instrumented moorings to increasing sampling frequency for chlorophyll; in any case, increase the sensitivity of chlorophyll measurement.

4.4. Benthos and Sediments

1. The benthic and sediment monitoring reveals no great changes overall and certainly nothing that could be attributed to the fish farming industry. This may be the case regardless of where the benthic/sediment stations are sited outside the immediate area of the farms. However, as discussed above, the fact that these stations were not picked to maximise the chance of observing subtle effects, should they be present, must be seen as a major weakness. We recommend that a study is conducted with the objective of remedying this situation, i.e. to place benthic/sediment monitoring stations in optimal locations and to discard stations which currently have little prospect of detecting any long-term changes that may be caused by fish farming. In designing such a study, the following points should be considered:
   - **i.** Several of the present stations in the most promising locations (i.e. with fines > 50%, Table 6) should be retained so as to maintain continuity of the time series. Stations with low proportions of fines (<50%, Table 6) should be discarded from future surveys unless there is some other compelling reason for retaining them.
   - **ii.** A study should be carried out that will use existing information (e.g. archived material, hydrodynamical model outputs) to identify the most likely places in the domain that sediments will accumulate. These candidate sites should then be evaluated with a field survey focussing on particle size and total organic carbon (or organic material by loss on ignition). A few of the softest stations identified should be selected and some long cores taken for establishment of the accumulation rate by dating and to determine if there is a biogeochemical signal that can be linked to the growth of the fish farming industry.
   - **iii.** If there are no truly accumulating stations to be found within the domain then we suggest that the number of stations be reduced to the eight stations with >50% fines from Table 6 in order to maintain the time series across the domain.
2. Some consideration should be given to the use of benthic indices. In addition, the advantages of moving towards a DNA metabarcoding methodology in terms of cost and speed should be investigated.
3. Some reef and Seagrass monitoring should be included in the BEMP, since these habitats may be impacted by fish nutrients or POM.

4.5. Modelling

The hydrodynamic and biogeochemical models developed by CSIRO and applied to the HEDC complement the observational BEMP. They have provided an understanding of the hydrodynamics of the water bodies, helped design the BEMP sampling strategy, and been used for an investigation of the likely consequences of nitrogen inputs in excess of the regulatory cap. They should continue to be used for diagnosis and prognosis.

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6. APPENDIX – STAKEHOLDERS CONSULTED

Stakeholder	Role	Contact date	Response received
Sean Riley	Head of Environment (Tassal)	26/01/2020	16/02/2021 (joint response)
Depha Miedecke	Technical/Strategy Manager (Petuna)	26/01/2021	
Adam Smark	Environmental Manager (Huon)	26/01/2021	
Jen Fry	Chief Advisor – Tasmanian Salmon Growers Association	02/02/2021 (after introduction at meeting on 1st)	
Dr Joseph Valentine	General Manager at Aquenal	26/01/2021	17/02/2021
Mr Sam Ibbott	Director Marine Solutions	26/01/2021	Outstanding
Dr Karen Wild-Allen	Principal Research Scientist at CSRIO	26/01/2021	04/02/2021
Dr Jeff Ross	Senior Research Fellow at UTAS	26/01/2021	01/02/2021
Dr Catriona Macleod	Centre Head – Ecology and Biodiversity	26/01/2021	Outstanding
Dr Ian Dutton	Director at Marine Resources	26/01/2021	11/02/2021 in meeting
Dr Christine Coughanowr	Independent Environmental Scientist	26/01/2021	02/03/2021