EVALUATION OF NERC CENTRES 2020: PLYMOUTH MARINE LABORATORY EVIDENCE SUBMISSION

Submitted February 2020

1. List of research outputs

Type of output	Title of output	Year	Journal title	DOI
D - Journal article	A general framework for aquatic biogeochemical models	2014	Environmental Modelling & Software	10.1016/j.envsoft.2014.04.002
D - Journal article	A small-scale, portable method for extracting microplastics from marine sediments	2017	Environmental Pollution	10.1016/j.envpol.2017.07.017
D - Journal article	Air exposure of coral is a significant source of dimethylsulfide (DMS) to the atmosphere	2016	Scientific Reports	10.1038/srep36031
D - Journal article	ALES: a multi-mission adaptive sub-waveform retracker for coastal and open ocean altimetry	2014	Remote Sensing of Environment	10.1016/j.rse.2014.02.008
D - Journal article	Antarctic sea ice region as a source of biogenic organic nitrogen in aerosols	2017	Scientific Reports	10.1038/s41598-017-06188-x
D - Journal article	Are Some Natural Environments More Psychologically Beneficial Than Others? The Importance of Type and Quality on Connectedness to Nature and Psychological Restoration	2017	Environment and Behavior	10.1177/0013916517738312
D - Journal article	Atmospheric deposition of methanol over the Atlantic Ocean	2013	Proceedings of the National Academy of Sciences of the United States of America	10.1073/pnas.1317840110
D - Journal article	Basin-scale phenology and climate variability in anadromous fishes: global seaward migration timing of the charismatic Atlantic salmon (Salmo salar)	2014	Global Change Biology	10.1111/gcb.12363
D - Journal article	Basking sharks and oceanographic fronts: quantifying associations in the north-east Atlantic	2015	Functional Ecology	10.1111/1365-2435.12423
D - Journal article	Biogeochemical controls of surface ocean phosphate	2019	Science Advances	10.1126/sciadv.aax0341
D - Journal article	Biogeochemical cycling of dissolved zinc along the GEOTRACES South Atlantic transect GA10 at 40o S	2014	Global Biogeochemical Cycles	10.1002/2013GB004637
D - Journal article	Biomass changes and trophic amplification of plankton in a warmer ocean	2014	Global Change Biology	10.1111/gcb.12562
D - Journal article	Both respiration and photosynthesis determine the scaling of plankton metabolism in the oligotrophic ocean	2015	Nature Communications	10.1038/ncomms7961
D - Journal article	Carbon sequestration in the deep Atlantic enhanced by Saharan dust	2017	Nature Geosciences	10.1038/ngeo2899
D - Journal article	Climate-Driven Change in the North Atlantic and Arctic Oceans Can Greatly Reduce the Circulation of the North Sea	2018	Geophysical Research Letters	10.1029/2018GL078878
D - Journal article	Coastal upwelling and downwelling forcing of circulation in a semi-enclosed bay: Ria de Vigo	2015	Progress in Oceanography	10.1016/j.pocean.2015.01.014

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D - Journal article	Co-liquefaction of macroalgae with common marine plastic pollutants	2019	ACS Sustainable Chemistry & Engineering	10.1021/acssuschemeng.8b06031
D - Journal article	Compartmentalized Calcium Signaling in Cilia Regulates Intraflagellar Transport	2013	Current Biology	10.1016/j.cub.2013.09.059
D - Journal article	Connected macroalgal-sediment systems: blue carbon and food webs in the deep coastal ocean	2019	Ecological Monograph	10.1002/ecm.1366
D - Journal article	Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios	2015	Science	10.1126/science.aac4722
D - Journal article	Contrasting responses of DMS and DMSP to ocean acidification in Arctic waters	2013	Biogeosciences	10.5194/bg-10-1893-2013
D - Journal article	Coralline algal structure is more sensitive to rate, rather than the magnitude, of ocean acidification	2013	Global Change Biology	10.1111/gcb.12351
D - Journal article	Decadal reanalysis of biogeochemical indicators and fluxes in the North West European shelf-sea ecosystem	2016	Journal of Geophysical Research-Oceans	10.1002/2015JC011496
D - Journal article	Deriving phytoplankton size classes from satellite data: Validation along a trophic gradient in the eastern Atlantic Ocean	2013	Remote Sensing of Environment	10.1016/j.rse.2013.02.013
D - Journal article	Detection and impacts of leakage from sub-seafloor deep geological carbon dioxide storage	2014	Nature Climate Change	10.1038/nclimate2381
D - Journal article	Dissecting the impact of CO2 and pH on the mechanisms of photosynthesis and calcification in the coccolithophore Emiliania huxleyi	2013	New Phytologist	10.1111/nph.12225
D - Journal article	Engineering the unicellular alga Phaeodactylum tricornutum for high-value plant triterpenoid production	2018	Plant Biotechnology Journal	10.1111/pbi.12948
D - Journal article	Estimating Oceanic Primary Production Using Vertical Irradiance and Chlorophyll Profiles from Ocean Gliders in the North Atlantic	2015	Environmental Science & Technology	10.1021/acs.est.5b00608
D - Journal article	Estimating the ecological, economic and social impacts of ocean acidification and warming on UK fisheries	2016	Fish and Fisheries	10.1111/faf.12183
D - Journal article	Frequent locations of ocean fronts as an indicator of pelagic diversity: application to marine protected areas and renewables	2014	Marine Policy	10.1016/j.marpol.2013.09.009
D - Journal article	Global ecological, social and economic impacts of marine plastic	2019	Marine Pollution Bulletin	10.1016/j.marpolbul.2019.03.022
D - Journal article	Global mismatch between fishing dependency and larval supply from marine reserves	2017	Nature Communications	10.1038/ncomms16039
D - Journal article	Global oceanic emission of ammonia: Constraints from seawater and atmospheric observations	2015	Global Biogeochemical Cycle	10.1002/2015gb005106
D - Journal article	Hidden impacts of ocean acidification to live and dead coral framework	2015	Proceedings of The Royal Society B	10.1098/rspb.2015.0990

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D - Journal article	Impact of El Nino Variability on Oceanic Phytoplankton	2017	Frontiers in Marine Science	10.3389/fmars.2017.00133
D - Journal article	Impact of missing data on the estimation of ecological indicators from satellite ocean-colour time-series	2014	Remote Sensing of Environment	10.1016/j.rse.2014.05.016
D - Journal article	Impacts of climate change on marine ecosystem production in societies dependent on fisheries	2014	Nature Climate Change	10.1038/NCLIMATE2119
D - Journal article	Insights from year-long measurements of air–water CH4 and CO2 exchange in a coastal environment	2019	Biogeosciences	10.5194/bg-16-961-2019
D - Journal article	Investigating a possible role for the bacterial signal molecules N-acylhomoserine lactones in Balanus improvisus cyprid settlement	2013	Molecular Ecology	10.1111/mec.12273
D - Journal article	Investigating microplastic trophic transfer in marine top predators	2018	Environmental Pollution	10.1016/j.envpol.2018.02.016
D - Journal article	Key Uncertainties in the Recent Air-Sea Flux of CO2	2019	Global Biogeochemical Cycles	10.1029/2018GB006041
D - Journal article	Krill (Euphausia superba) distribution contracts southward during rapid regional warming	2019	Nature Climate Change	10.1038/s41558-018-0370-z
D - Journal article	Krill faecal pellets drive hidden pulses of particulate organic carbon in the marginal ice zone	2019	Nature Communications	10.1038/s41467-019-08847-1
D - Journal article	Long-term impacts of rising sea temperature and sea level on shallow water coral communities over a ~40 year period	2019	Scientific Reports	10.1038/s41598-019-45188-x
D - Journal article	Marine ecosystem services: linking indicators to their classification	2015	Ecological Indicators	10.1016/j.ecolind.2014.09.026
D - Journal article	Mechanisms shaping size structure and functional diversity of phytoplankton communities in the ocean	2015	Scientific Report	10.1038/srep08918
D - Journal article	Mesoscale fronts as foraging habitats: composite front mapping reveals oceanographic drivers of habitat use for a pelagic seabird	2014	Journal of the Royal Society Interface	10.1098/rsif.2014.0679
D - Journal article	Microplastic ingestion by zooplankton	2013	Environmental Science and Technology	10.1021/es400663f
D - Journal article	Modelling the effects of climate change on the distribution and production of marine fishes: accounting for trophic interactions in a dynamic bioclimate envelope model	2013	Global Change Biology	10.1111/gcb.12231
D - Journal article	Monsoon oscillations regulate fertility of the Red Sea	2015	Geophysical Research Letters	10.1002/2014GL062882
D - Journal article	Ocean acidification and hypoxia alter organic carbon fluxes in marine soft sediments	2019	Global Change Biology	10.1111/gcb.14806
D - Journal article	Ocean acidification and rising temperatures may increase biofilm primary productivity but decrease grazer consumption	2013	Philosophical Transactions of the Royal Society of London Series B	10.1098/rstb.2012.0438

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D - Journal article	Ocean acidification can mediate biodiversity shifts by changing biogenic habitat	2017	Nature Climate Change	10.1038/nclimate3161
D - Journal article	Ocean acidification through the lens of ecological theory	2015	Ecology	10.1890/14-0802.1
D - Journal article	Ocean acidification with (de)eutrophication will alter future phytoplankton growth and succession	2015	Proceedings of The Royal Society B	10.1098/rspb.2014.2604
D - Journal article	Ocean-colour products for climate-change studies: what are their ideal characteristics?	2017	Remote Sensing of Environment	10.1016/j.rse.2017.04.017
D - Journal article	Ocean-wide tracking of pelagic sharks reveals extent of overlap with longline fishing hotspots	2016	Proceedings of the National Academy of Sciences of the United States of America	10.1073/pnas.1510090113
D - Journal article	Optical types of inland and coastal waters	2017	Limnology and Oceanography	10.1002/lno.10674
D - Journal article	Pan genome of the phytoplankton Emiliania underpins its global distribution	2013	Nature	10.1038/nature12221
D - Journal article	Phytoplankton phenology indices in coral reef ecosystems: Application to ocean-color observations in the Red Sea	2015	Remote Sensing of Environment	10.1016/j.rse.2015.01.019
D - Journal article	Prediction of unprecedented biological shifts in the global ocean	2019	Nature Climate Change	10.1038/s41558-019-0420-1
D - Journal article	Production of methanol, acetaldehyde and acetone in the Atlantic Ocean	2013	Geophysical Research Letters	10.1002/grl.50922
N - Research report for external body	Projected changes in global and national potential marine fisheries catch under climate change scenarios in the twenty-first century	2018		
D - Journal article	Quantification of glycine betaine, choline and TMAO in seawater particulates: minimisation of seawater associated ion suppression	2016	Analytica Chimica Acta	10.1016/j.aca.2016.07.016
D - Journal article	Regional adaptation defines sensitivity to future ocean acidification	2017	Nature Communications	10.1038/ncomms13994
D - Journal article	Remotely Sensing the Biophysical Drivers of Sardinella aurita Variability in Ivorian Waters	2018	Remote Sensing	10.3390/rs10050785
D - Journal article	Satellite estimates of net community production indicate predominance of net autotrophy in the Atlantic Ocean	2015	Remote Sensing of Environment	10.1016/j.rse.2015.03.017
D - Journal article	Scaling up experimental ocean acidification and warming research: from individuals to the ecosystem	2014	Global Change Biology	10.1111/gcb.12675
D - Journal article	Seasonal ITCZ migration dynamically controls the location of the (sub-)tropical Atlantic biogeochemical divide	2014	Proceedings of the National Academy of Sciences	10.1073/pnas.1318670111

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D - Journal article	Sensing coral reef connectivity pathways from space	2017	Scientific reports	10.1038/s41598-017-08729-w
D - Journal article	Sensitivity to ocean acidification parallels natural pCO2 gradients experienced by Arctic copepods under winter sea ice	2013	Proceedings of the National Academy of Sciences of the United States of America	10.1073/pnas.1315162110
D - Journal article	Solutions for ecosystem-level protection of ocean systems under climate change	2016	Global Change Biology	10.1111/gcb.13423
D - Journal article	Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity	2017	Nature Ecology and Evolution	10.1038/s41559-017-0084
D - Journal article	SST Dynamics at Different Scales: Evaluating the Oceanographic Model Resolution Skill to Represent SST Processes in the Southern Ocean	2019	Journal of Geophysical Research: Oceans	10.1029/2018JC014791
D - Journal article	Submesoscale Rossby Waves on the Antarctic Circumpolar Current	2018	Science Advances	10.1126/sciadv.aao2824
D - Journal article	Substantial energy input to the mesopelagic ecosystem from the seasonal mixed-layer pump	2016	Nature Geoscience	10.1038/ngeo2818
D - Journal article	Substantial Seasonal Contribution of Observed Biogenic Sulfate Particles to Cloud Condensation Nuclei	2018	Scientific Reports	10.1038/s41598-018-21590-9
D - Journal article	Surface ocean carbon dioxide during the Atlantic Meridional Transect (1995-2013); evidence of ocean acidification	2017	Progress in Oceanography	10.1016/j.pocean.2016.08.005
D - Journal article	Sustainability and life cycle assessment (LCA) of macroalgae-derived single cell oils	2019	Journal of Cleaner Production	10.1016/j.jclepro.2019.05.315
D - Journal article	The Atlantic Ocean surface microlayer from 50 degrees N to 50 degrees S is ubiquitously enriched in surfactants at wind speeds up to 13ms-1	2017	Geophysical Research Letters	10.1002/2017GL072988
D - Journal article	The cost of reducing the North Atlantic Ocean biological carbon pump	2016	Frontiers in Marine Science	10.3389/fmars.2016.00290
D - Journal article	The Ocean Colour Climate Change Initiative: III. A round-robin comparison on in-water bio-optical algorithms	2015	Remote Sensing of Environment	10.1016/j.rse.2013.09.016
D - Journal article	The open-ocean missing backscattering is in the structural complexity of particles	2018	Nature Communications	10.1038/s41467-018-07814-6
D - Journal article	The origin of carbon isotope vital effects in coccolith calcite	2017	Nature Communications	10.1038/ncomms14511
D - Journal article	The value of carbon sequestration and storage in coastal habitats	2014	Estuarine, Coastal and Shelf Scienc	10.1016/j.ecss.2013.11.022
D - Journal article	Underway spectrophotometry along the Atlantic Meridional Transect reveals high performance in satellite chlorophyll retrievals	2016	Remote Sensing of Environment	10.1016/j.rse.2016.05.005

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D - Journal article	Unstructured Grid Modelling of Offshore Wind Farm Impacts on Seasonally Stratified Shelf Seas	2016	Progress in Oceanography	10.1016/j.pocean.2016.04.004
D - Journal article	Valuing conservation benefits of an offshore marine protected area	2014	Ecological Economics	10.1016/j.ecolecon.2014.10.006
D - Journal article	Valuing the health benefits of physical activities in the marine environment and their importance for marine spatial planning	2016	Marine Policy	10.1016/j.marpol.2015.10.009
D - Journal article	Vulnerability of coastal ecosystems to changes in harmful algal bloom distribution in response to climate change: projections based on model analysis	2014	Global Change Biology	10.1111/gcb.12662
D - Journal article	Why artificial light at night should be a focus for global change research in the 21st century	2017	Global Change Biology	10.1111/gcb.13927
D - Journal article	Wind speed and sea state dependencies of air-sea gas transfer: Results from the high wind speed gas exchange study (HiWinGS)	2017	Journal of Geophysical Research: Oceans	10.1002/2017JC013181
D - Journal article	Winter weather controls net influx of atmospheric CO2 on the northwest European shelf	2019	Scientific Reports	10.1038/s41598-019-56363-5
D - Journal article	Zooplankton gut passage mobilises lithogenic iron for ocean productivity	2016	Current Biology	10.1016/j.cub.2016.07.058

2. Impact case studies

Centre: **Plymouth Marine Laboratory (PML)**

Title of case study: **Valuing marine ecosystem benefits to inform policy and management approaches and provide evidence for the designation of protected areas**

1. Summary of the impact

The marine environment supports human wellbeing and economic growth, yet is subject to multiple pressures that reduce its ability to do so. In order to make informed management decisions a common currency is needed to assess and compare the value of benefits derived from the sea. PML researchers were the first to identify and systematically value these benefits and thus quantify their significance. These valuations enabled a whole-ecosystem approach that has transformed management and governance and provided evidence to underpin the designation of Marine Conservation Zones. PML research was fundamental to the National Ecosystem Assessment which informed government policy including the UK's Natural Environment White Paper and 25 Year Environment Plan. The approaches used have informed other countries' ecosystem assessments and the strategies of UK Government departments.

2. Underpinning research

Natural capital accounting is a way of considering nature as an asset that provides benefits to people and the economy. The ecosystem services that natural capital provides, such as food and climate regulation, support our health and wellbeing and underpin economic activity. To understand the comparative value of the different benefits provided by the marine environment, PML used natural and social science to ensure that all benefits, including those without a direct market value, are included in decision making.

In 2003, when use of the ecosystem services concept was still in its infancy, Environmental Economist Dr Nicola Beaumont (PML since 2002) was the first to identify and calculate the values of a wide range of services provided by the UK marine environment. As a member of a Prime Minister's Strategy Unit, Dr Beaumont's work contributed to the Cabinet Office publication; *Net benefits: a sustainable and profitable future for UK fishing* [3.1]. Dr Beaumont's valuations highlighted that some key ecosystem services had a higher economic value than commercial fishing. This research underpinned recommendations to the Government on how to achieve the best package of policy reforms. The aim being to ensure that the fishing industry is profitable and sustainable, whilst minimising impact on other valuable services of social and economic importance.

In 2006 Dr Beaumont co-authored the most highly cited paper on marine ecosystem services [3.2]. This paper concluded that marine biodiversity loss is impairing the ocean's capacity to provide food, maintain water quality, and recover from disturbances. She also led a team of PML researchers in an economic valuation for the Department for Environment, Food and Rural Affairs (Defra) that informed the need for further protection of the marine environment [3.3; 3.4]. The research provided monetary values of the services resulting from marine biodiversity in UK waters and innovatively used them to demonstrate the changes in value under future conditions of environmental change. The research valued UK marine biodiversity at an estimated GBP2,670,000,000,000, a figure that has been used in Government reports including *Future of the Sea: marine biodiversity* [3.5]. The research also identified non-use values of marine resources, based on the benefits derived purely from the ongoing existence of a species or habitat; these were calculated to be worth at least GBP500,000,000 to the UK each year.

In 2007 Dr Beaumont and Dr Melanie Austen (PML since 1989, Professor from 2014) led an international team to identify and define the services provided by marine ecosystems. This resulted in a paper which set out a framework for the assessment of goods and services and provided examples using a variety of case studies. It demonstrated how the approach can integrate the demands of society, the economy and the environment into management. The development of this approach was fundamental to the National Ecosystem Assessment (NEA).

The first of its kind in the world, the NEA appraised the UK's natural environment in terms of the benefits it provides to society and economic prosperity. It remains the most comprehensive assessment of the UK's natural resources ever undertaken. Dr Austen was appointed to the Expert Panel of Phase 1 of the NEA and was the coordinating lead author of its *Marine* chapter [3.6], which included 5 members of PML staff as lead or contributing authors. Dr Beaumont led the economic analysis of coastal margins and marine habitats, providing values to underpin the chapter she co-authored; *Economic Values from Ecosystems* [3.7]. The Marine chapter of the NEA drew on much of PML's published research referring to 26 papers from 29 different PML researchers as lead or co-authors.

3. References to the underpinning work

PML authors are highlighted in bold type, citation numbers from Web of Science 7 January 2020.

3.1. Cabinet Office. 2004. *Net benefits: a sustainable and profitable future for UK fishing*. Prime Minister's Strategy Unit: London, UK, 167pp. http://www.eurocbc.org/netbenefits.pdf

3.2. Worm, B., Barbier, E.B., **Beaumont, N.**, Duffy, J.E., Folke, C., Halpern, B.S. *et al.* 2006. Impacts of biodiversity loss on ocean ecosystem services. *Science*, 314(5800), 787-790. doi:10.1126/science.1132294 [2221 citations].

3.3. **Beaumont, N.**, **Townsend, M.**, **Mangi, S.**, **Austen, M.C.** 2006. *Marine biodiversity: an economic valuation. Building the evidence base for the Marine Bill*. Department for Environment, Food and Rural Affairs (Defra), 64pp. http://randd.defra.gov.uk/Document.aspx?Document=WC04029_4013_FRP.pdf

3.4. **Beaumont, N.J.**, **Austen, M.C.**, **Mangi, S.C.**, **Townsend, M.** 2008. Economic valuation for the conservation of marine biodiversity. *Marine Pollution Bulletin*, 56(3), 386-396. doi:10.1016/j.marpolbul.2007.11.013 [145 citations].

3.5. Foresight: Government Office for Science. 2017. *Future of the sea: marine biodiversity*. Government Office for Science: London, UK, 35pp. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/663897/Future_of_the_Sea_-_Marine_Biodiversity_Final.pdf

3.6. **Austen, M.C.**, Malcolm, S.J., Frost, M., **Hattam, C.**, **Mangi, S.**, Stentiford, G. *et al.* 2011. Chapter 12: Marine. In *The UK National Ecosystem Assessment technical report*, United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, UK, 459-498 http://uknea.unep-wcmc.org/Resources/tabid/82/Default.aspx

3.7. Bateman, I.J., Abson, D., **Beaumont, N.**, Darnell, A., Fezzi, C., Hanley, N. *et al.* 2011. Chapter 22: Economic values from ecosystems. In *The UK National Ecosystem Assessment technical report*, UN Environment Programme World Conservation Monitoring Centre, Cambridge, UK, 459-498 http://uknea.unep-wcmc.org/Resources/tabid/82/Default.aspx

4. Details of the impact

Providing underpinning evidence for legislation and conservation designations

The Marine Bill was formed in 2008 to establish a new framework for the management of UK seas and improve marine planning. Dr Beaumont's 2006 report [3.3] was written to provide evidence for the Bill and was specifically referenced in the Impact Assessment, which sets out the costs and benefits of its implementation. In particular, it was demonstrated that the economic benefit derived from the Bill would be significantly increased if Dr Beaumont's non-use values were included [5.1]. Dr Austen presented written and oral evidence to the House of Lords and House of Commons Joint Committee on the Draft Bill in July 2008. The Bill was officially adopted as the Marine and Coastal Access Act (MCAA) in 2009. The MCAA includes a legal duty to designate Marine Conservation Zones (MCZs) to ensure the UK meets national and international commitments, such as the EU Marine Strategy Framework Directive.

To date 91 MCZs have been designated in waters around England over 3 phases (2013, 2016, and 2019). Dr Beaumont's work [3.3; 3.4] was used to support the economic case for these designations underpinning the net present value calculations in the Government's Impact Assessment for each tranche of designations [5.2]. The Impact Assessments also drew on evidence from the NEA with 10 references to the *Marine* chapter [3.6] led by Dr Austen. The Impact Assessment for the third tranche of designations in 2019 also used the NEA's economic

analysis of ecosystem services provided by UK coastal margin and marine habitats, which was led by Dr Beaumont. For example, PML's calculations of the value of regulating services were used to demonstrate the existing benefits of the UK marine environment and provided evidence of the need for further designations. PML's work was used to show that protecting a wide range of species and habitats can increase resilience to natural and human pressures.

The designations complete the UK Blue Belt providing protection for 22,000,000ha of English waters and Northern Ireland offshore waters - nearly twice the size of England. This completes the Government's contribution to the ecologically coherent network of protected areas in the northeast Atlantic in terms of the representation of species and habitats.

"*Through the Marine and Coastal Access Act 2009, our seas have become a global exemplar of marine conservation. We are leading the world in developing a marine planning system and in encouraging socioeconomic activities such as fishing to be seen as part of the solution to the environmental challenges that our seas face*". HM Government, The Natural Choice [5.3]

Shaping national policy

PML scientists had key roles in the development and delivery of the NEA, which formed the basis of the 2011 Natural Environment White Paper, *The Natural Choice: securing the value of nature* [5.3]. The White Paper sets out the principles for incorporating ecosystem services and their value within conventional government decision-making. It states that "*the results of this research [NEA] deserve to be widely known; they are the reason for many of the actions proposed in this White Paper*". The holistic approach of the NEA, underpinned by PML's contributions to the marine and coastal aspects, is conveyed in the methodology of the White Paper. This policy document includes PML research, such as marine ecosystem trends, and refers to Dr Beaumont's valuations of coastal wetlands, recognizing the valuable natural functions these habitats provide.

The White Paper provided the legislation for including natural capital within the UK Environmental Accounts, laid the way for the UK's 25 Year Environment Plan (25YEP) and established the Natural Capital Committee (NCC) to advise the Government on environmental assets. As the first and only marine representative on the NCC, Dr Austen ensured that the marine environment was fully incorporated into their 2019 Annual Report and led their first marine advisory paper to the Government. The White Paper influenced the content of the National Planning and Policy Framework, delivered the Biodiversity Strategy for England and set-up Nature Improvement Areas and Local Nature Partnerships [5.4].

"*The ecosystem services valuation work carried out as part of the UK NEA represents a clear example of where valuation activities have contributed to a decision-making process. The results of this valuation work made ministers in the UK realise that a 'business as usual' path was not an optimal route to follow in terms of the benefits and services provided by the natural environment. The impact achieved by the publication of the UK NEA was that it fed directly into a Natural Environment White Paper and many other policy initiatives".* European Commission [5.5]

The 25YEP [5.6] states that the NEA *"has been hugely influential in the development of natural environment policy in England, the devolved administrations, and internationally"* and a second assessment is planned for 2022.

Informing international assessment approaches

The first of its kind in the world, the UK NEA inspired and informed similar approaches all over the world, influencing the way other nations approach their own assessments. Dr Beaumont is directly cited in the NEA for Norway and France and at a global level in The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services' Global Assessment [5.7]. In the EU, the UK NEA has been used as an evidence source and a methodology for the EU Biodiversity Strategy [5.8]. The NEA currently being developed by Singapore is drawing on the approaches used in the UK NEA. In particular they are using the marine and coastal chapters to inform their approach.

"Singapore took lessons from the approaches applied by Dr Beaumont and Prof Austen of PML as lead authors for the Marine and Coastal chapters of the NEA. This helped us refine the scope of our assessment and what ecosystem components should be assessed and how. We took lessons from the valuation approaches applied and choices of indicators. This saved us an invaluable amount of time, not having to create this framework from scratch and learning from the previous discussions around different approaches." Project Coordinator, Natural Capital Singapore [5.9].

Shaping the approach of Government departments

The NEA was revolutionary in its approach to assessing the UK's natural environment by considering the value of the services it provides. The approach was cemented into UK policy through the Natural Environment White Paper and radiated out to key Government departments. Natural capital now features in the strategies for the Joint Nature Conservation Committee (JNCC) and Natural England. The JNCC 2017-2020 strategy *'supports new policy approaches based on the concepts of natural capital and integrated management of natural resources. These concepts will shape our future work'* [5.10]. Natural England's Conservation Strategy for the 21st century calls the concept of natural capital a '*powerful new tool'* that *'offers the potential to make environmental planning central to local and national decision-making'* [5.11].

"*The NEA, because it was compiled by a wide community of scientists and produced coherent, quantified evidence showing the values to society of natural ecosystems, was a key part of a cultural shift to focus on people, as much as other species, as beneficiaries of nature conservation. The natural capital approach is now pivotal to much of JNCC's activity. Understanding the economic value of, for example, flood protection and carbon capture and storage by coastal habitats is leading to new approaches such as restoration of salt marshes, seagrass and oyster beds.*" Marine Natural Capital Leader, JNCC [5.12]

Informing delivery of the Government's 25 Year Environment Plan

The 25YEP explicitly states that "*over the coming years the UK intends to use a 'natural capital' approach as a tool to help us make key choices and long-term decisions*". The North Devon Marine Pioneer is 1 of 4 Government initiatives that have been set-up to inform delivery of the 25YEP and test the application of a natural capital approach. PML has been fundamental to the delivery of the Pioneer through involvement in the NERC-funded South West Partnership for Environment & Economic Prosperity (SWEEP).

"*PML's contribution to the Marine Pioneer has been substantial, building the evidence base and co-developing knowledge and tools to shape and progress the pioneer. The pioneer is a key programme to test delivery of the Government's 25YEP, the approaches developed will help the Government work towards enhancing nature for the next generation and achieving environmental net gain*", Marine Pioneer Programme Lead, MMO [5.13].

Through SWEEP, Sustainability Appraisals were identified as a key legislative process where natural capital can inform decision making. Dr Tara Hooper (PML since 2012) has developed a methodology for incorporating natural capital into these appraisals which evaluate the economic, environmental and social effects of a local plan. This methodology, which is now being applied to local and marine planning in the southwest, had not previously been attempted for either marine or terrestrial environments. Through this work Dr Hooper has been influential in the development of the North Devon Marine Natural Capital Plan, the first ever local marine spatial plan using a natural capital approach, which is informing the management strategy of the UNESCO Biosphere Reserve.

"PML has been instrumental in shaping the development of the Marine Natural Capital Plan for North Devon, changing our approach to management of the UNESCO World Biosphere Reserve. The experience we have gained from working with PML means that we can share the good practice with other UNESCO sites around the world as part of the intergovernmental science programme". Biosphere Reserve Co-ordinator and Services Manager [5.14].

Adding value to marine management

PML's research has brought marine ecosystem services valuation into the mainstream. This approach has informed coastal site management at the local level including the Tamar Estuary Management Plan and North Devon Biosphere Reserve.

In 2016 PML hosted a workshop for regional site managers on applying the ecosystem services approach. As a result of the workshop and ongoing collaboration, a section on 'Nature's Value' was added to the Exe Estuary Management Plan [5.15]. For the first time it details the benefits the estuary provides to society and how valuation of these services enables direct comparison of the economic and societal impact of different uses. It uses findings from the NEA to provide evidence throughout the report and specifically acknowledges PML's contribution [5.15].

"*The NEA has led to an increased understanding of the significance of safeguarding ecosystems goods and services and the usefulness of an ecosystem based approach for management*". Tamar Estuary Management Plan [5.16].

5. Sources to corroborate the impact

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Centre: **Plymouth Marine Laboratory (PML)**

Title of case study: **Satellite-derived ocean front maps inform the designation of national and international areas for marine protection**

1. Summary of the impact

Our oceans face multiple stressors due to climate change, overexploitation and pollution. Area-based conservation approaches are used throughout the world but do not always protect highly mobile marine fauna, such as basking sharks and turtles. PML has provided a means to address this challenge by using satellite data to create maps that identify hotspots of marine life. These maps were the only datasets selected by the UK government to represent mobile species in the planning of marine conservation areas. This resulted in PML's research informing the designation of 1,884,700ha of Marine Protected Areas around the UK. The research has also been used on a global scale to help to define the boundaries of 60,133,500ha of Ecologically or Biologically Significant Marine Areas that contribute to the protection and sustainable use of marine biodiversity.

2. Underpinning research

The UK government is required by law to create an ecologically-coherent network of Marine Protected Areas (MPAs) to protect the diversity of species that live in the ocean. This is a considerable challenge for the pelagic (water column) ecosystem that is constantly changing in time and space and the highly mobile species that live within it. Management approaches that rely on defining fixed areas of the ocean need to take into account the key areas that mobile species frequently use as feeding grounds. Using satellite data, PML have developed a technique to identify the areas of greatest value to mobile species to inform the development of this network. PML's solution provides a cost-effective, readily available and reliable source of information that can address this policy need.

Starting in 1997, the Remote Sensing Group at PML developed the capability to automatically process large quantities of satellite data into ocean temperature and colour products. These can be used for monitoring coastal and oceanic processes across the globe. Dr Peter Miller (PML since 1997) led a team that used this capability to develop novel techniques for visualising ocean fronts - dynamic structures where two water masses of different temperature, density or other property meet. These areas benefit from increased nutrient supply and hence greater biological productivity. Dr Miller first combined the location, strength and persistence of all fronts observed over several days into a single composite front map in 2004 using 1km resolution data [3.1]. Uniquely, Dr Miller's methodology allowed the visualisation of both dynamic and stable fronts, generating metrics to indicate their temperature gradients, persistence and spatial variability over time [3.2].

Soon after the technique was developed, the University of Aberdeen was studying satellite tracking of basking shark movements off Scotland. Dr Miller analysed satellite data to compare composite front maps with the tracking data to provide further evidence of the link between fronts and key feeding sites for marine megafauna. The research confirmed that the shark was swimming parallel to a front, and believed to be feeding along the line of the front [3.3]; this research emphasised the importance of fronts for supporting marine life. The enhanced nutrient supply found at fronts supports increased abundance of plankton, which in turn supports higher trophic levels, demonstrating that fronts can be used as a proxy for biodiversity [3.4].

In 2010 PML contributed to a Department for Environment, Food and Rural Affairs (Defra) project to collate data for the planning of a network of MPAs. Dr Miller's team produced one of the final project reports and a key data layer on ocean fronts, used as a surrogate for hotspots of pelagic diversity for the UK continental shelf [3.5]. The report described the methodology used to develop the data layer and provided direction on interpreting and applying front maps to inform the designation of MPAs. This was the first time that ocean front maps had been compiled to guide the process of defining protected areas.

Ten years of satellite data, incorporating more than 30,000 images, were processed to encompass interannual variability. Ocean fronts were detected on every scene and combined to generate monthly front maps displaying the location, gradient, persistence and proximity of all fronts over a

given time-period. The maps were then combined into a seasonal ocean front data layer providing a robust indication of where pelagic diversity hotspots occur throughout the year (Figure 1).

Further advancement to this technique came in 2012 when Dr Miller and Dr Xu, in collaboration with Scottish Natural Heritage, successfully applied front detection and aggregation techniques to higher-resolution (300m) satellite data in Scottish coastal waters. This allowed smaller frontal zones or those in close proximity to the coast to be detected for the first time as this had not been possible using medium resolution data. Seasonal frequency front maps, derived from both chlorophyll and sea surface temperature data, revealed a number of key frontal zones. Some of which were identifiable due to new insights into the sediment and plankton dynamics provided by the higher-resolution data [3.6].

Since his formative paper in 2004, Dr Miller has authored 30 papers on ocean fronts which have been cited widely. His method has been used in a wide range of applications from cetacean habitat modelling, seabird behaviour, conservation of marine megafauna, to the effects of renewable energy installations on biodiversity. This work has been supported by PML colleagues including Dr Saux-Picart, S. (2008-2013), Christodoulou, S (2009-2011) and Xu, W (2012-2014).

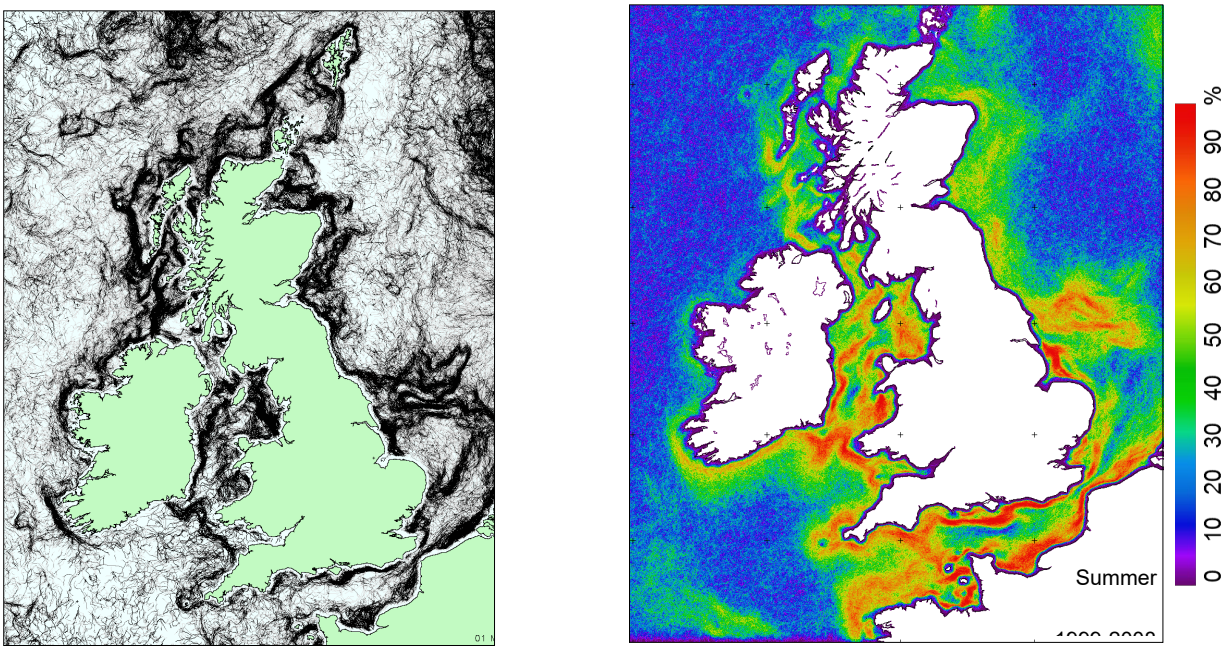

Figure 1. Example monthly front map (left) used to generate a 10-year front frequency map (right)

3. References to the underpinning work

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4. **Details of the impact**

Producing key evidence for the designation of national Marine Protected Areas

Ocean front maps, compiled by Dr Miller, were the only datasets selected by Defra to represent mobile species in the planning of MPAs in the UK [3.4]. The UK and Scottish governments have a duty to develop a network of MPAs, under the EC Marine Strategy Framework Directive, UN Convention on Biological Diversity (CBD) and UN Sustainable Development Goal 14.5 (to conserve at least 10% of coastal and marine areas by 2020). PML's maps informed the designation of 1,884,700ha of protected ocean, contributing to an ecologically coherent network of MPAs around the UK [5.1].

In 2010 the UK government established four regional projects in England and Wales to work with local stakeholders to develop proposals for new MPAs. Each of these groups was provided with a range of data including the ocean front maps to ensure that they had the best available information to identify the most suitable areas to put forward. *"The ocean front maps were used by all of the regional Steering Groups as part of discussions to determine the key areas to put forward for protection. They provided a strong indication of the importance of sites for mobile species and pelagic biodiversity and as such were tremendously important."* Project Manager, Finding Sanctuary [5.2].

PML's ocean front maps influenced decision making in all of the regional MPA projects with 16 of the 46 proposed MPAs in the first round of designations specifically mentioning ocean fronts in their assessments [5.1]. To date the ocean front maps have informed the designation of 7 MPAs, ensuring the protection of an area of more than 397,000ha [5.1]. By providing evidence of the spatial variability of fronts over time, PML helped to inform the government of the appropriate size and boundaries of the designated areas.

The Scottish government used ocean front maps to inform the MPA designation process [5.3], in particular the high-resolution maps compiled in 2012. *"Oceanic fronts were one of just five large-scale features selected for protection as part of the Scottish MPA network. Dr Miller's reports contributed towards their selection – they provided the evidence that fronts are persistent features over time and space and were used to inform the definition of fronts for the process. The data products from these reports were used to underpin the inclusion of fronts in the Clyde Sea Sill MPA (designated 2014), Southern Trench proposed MPA and the Sea of the Hebrides proposed MPA (consulted on in 2019)."* Scottish Natural Heritage [5.4].

The MPAs in Scottish waters informed by Dr Miller's maps will cover a combined area of 1,328,700ha. In all three cases fronts have been recognised for their importance as features that contribute to the overall health and biodiversity of the marine environment [5.1]. The MPAs ensure protection for key species such as black guillemots (Clyde Sea Sill), minke whales (Southern Trench and Sea of the Hebrides) and basking sharks (Sea of the Hebrides). Fisheries management measures have been implemented for the Clyde Sea Sill MPA, similar management measures will follow for the other MPAs once designated (decision due in Spring 2020). The management measures are used to limit the use of fishing gear that would adversely impact the habitat or mobile animals.

The overall benefits of the Scottish network of MPAs was estimated to be at least GBP6,300,000,000 over 20 years [5.5]. Assessed in a report for Scottish Environment LINK, the calculation was based on the types of habitat in each MPA and the expected change in value of the goods and services under the proposed management scenarios. The methodology and

valuations were underpinned by PML research published by Dr Beaumont (PML since 2002) who was the first researcher to define and value the benefits provided by the marine environment [5.6].

Informing the protection of international marine sites

Ocean front maps were used on a global scale as evidence in 4 workshops in 2013. Led by the UN Convention on Biological Diversity (CBD) the workshops identified Ecologically or Biologically Significant marine Areas (EBSAs). Covering national, transboundary, or areas beyond national jurisdiction, EBSAs contribute to the protection and sustainable use of marine biodiversity by describing areas of particular significance. The scientific criteria for identifying EBSAs include biological productivity and diversity; both of which reference fronts as example indicators [5.7].

PML's maps directly influenced the selection of EBSAs in the Eastern Tropical and Temperate Pacific Regional Workshop and North Pacific Regional Workshop. "*The maps were used, along with sea turtle inter-nesting data, to extend the initial offshore proposal for the Costa Rica Dome to meet the coast along the Gulf of Papagayo"* University of Duke [5.8], and *"to help identify a boundary for the Carnegie Ridge and Equatorial front EBSA description"* University of Duke [5.8]. These two areas equate to 60,133,500ha of protected marine habitats. The EBSAs have been approved by the UN and used to inform national planning processes and to secure international funding [5.9]. For example, The Global Ocean Biodiversity Initiative has been awarded a grant of EUR5,200,000 (05-2016) to support the EBSA process. Part of this funding has been used to conduct oceanographic surveys and create an Atlas of the Costa Rica Dome, part of the Upwelling System of Papagayo EBSA. An analysis of possible governance schemes for the area is under review which will form the basis for negotiations with regional authorities to define an appropriate governance regime for the region [5.10].

In the most recent round of designations, front maps featured prominently in the description of the North Atlantic Current and frontal system at the mid-Atlantic EBSA. This is an area of high productivity, with a high density of foraging activity, home to 21 species of seabird including the endangered Zino's Petrel and Bermuda Petrel. The EBSA description was approved at the NE Atlantic workshop and will now go forward for approval by the CBD Conference of Parties in 2020.

"PML's front maps underpinned the description of the Mid-North Atlantic frontal system EBSA. This site corresponds to an important foraging area for 21 seabird species, including 6 globally threatened species as defined by International Union for Conservation of Nature and Natural Resources Red List. The maps were crucial for defining the area including identifying persistent and ephemeral hydrographic features" BirdLife International [5.11].

The benefits of Marine Protected Areas

MPAs are primarily policy tools for conservation, used to protect and enhance marine biodiversity. However, it has been shown that they can also deliver tangible economic benefits as well as other societal benefits through ecosystem services and climate change mitigation. In 2017 a European Commission study, co-led by PML's Dr Caroline Hattam (PML since 2008), reviewed the economic benefits of MPAs, illustrated by case studies from across Europe for a range of sectors [5.12].

Fisheries were shown to benefit through improved fish stocks, both for fisheries still permitted inside the MPA as well as outside due to a spill-over effect. In Italy, MPAs were demonstrated to have supported stock improvements with increases in catch rates of 100% for some species, and catch per unit effort inside the MPA double that of the rate outside. The spill-over effect was shown to improve the yield of spiny lobsters by 10% annually in a Spanish MPA. In some areas, such as Lyme Bay in the UK, the MPA has even resulted in a higher market value of products to boost income for local fishermen.

MPAs can facilitate increases in tourism and changes in visitor behaviour that result in higher revenues, increased jobs and additional livelihood opportunities. For example, income generated through tourism inside the Lyme Bay MPA increased by GBP1,500,000 within 3 years of its designation. Acknowledging the study, the European Commission said that MPAs generate "*tangible economic growth"* [5.13].

5. Sources to corroborate the impact (indicative maximum of ten references)

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appropriate evidence, as corroboration of the impact of PML research in the MPA planning process, 313pp. https://www.pml.ac.uk/People/Science_Staff/Dr_Peter_Miller/MPA_selection.pdf

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Centre: **Plymouth Marine Laboratory (PML)**

Title of case study: **Shaping policy and reducing marine plastic pollution**

1. Summary of the impact

Plastic debris is a widespread and persistent pollutant in the marine environment, which poses a considerable risk to marine organisms and has economic repercussions for society. PML was the first organisation to identify that microplastics are damaging zooplankton, the most numerous animals on Earth and a key link in oceanic food chains. This pioneering work underpinned UK legislation to ban microplastic beads from the manufacture of wash-off cosmetics; a landmark ruling which ensures 4,000 fewer tonnes of plastic enter our oceans every year. The research has also been used as evidence for bans in 4 other countries and is informing debate in Europe on an EU-wide restriction of intentionally added microplastics. PML's outreach activities have reached global audiences contributing to surging public awareness that is putting pressure on policymakers and manufacturers to reduce plastic waste.

2. Underpinning Centre activities

The potential environmental cost of marine plastic currently in the ocean has been valued by PML as at least GBP380,000,000,000 each year based on the effect it has on the oceans' ability to provide goods and services for humankind [3.1]. The most numerous plastic in the world's oceans are small pieces less than 5mm in size; these 'microplastics' are either manufactured to be microscopic in size, for use in cosmetic or industrial applications, or derive from the fragmentation of larger plastic debris following prolonged degradation.

PML's microplastics team comprises Dr Pennie Lindeque, Dr Matthew Cole and a cohort of students (4 PhD, 6 Masters and 4 placement students since 2014). Their unique area of expertise is the study of the effects of microplastics on zooplankton. Dr Lindeque (PML since 1995; Professor from 2019) has led this team since 2010, and in the past 5 years has overseen 10 microplastics research grants and 4 studentships, valued at more than GBP1,000,000 to PML, which has resulted in the publication of 31 research papers. Dr Cole undertook his PhD at PML (2010–2014), and continued as a postdoc on a joint NERC research grant between PML and the University of Exeter (2014–2017) before being employed by PML in 2017. PML collaborates with 4 UK Universities to host PhD students in the area of microplastics; these universities act as the awarding body and provide additional supervision and facilities. The microplastics team has worked with colleagues across PML to bring together expertise from different disciplines to broaden the research scope, including social scientists (Austen, Beaumont), ecologists (Fileman, Queiros) and environmental modellers (Clark, Artioli, Torres).

PML was the first to evidence that microplastics are ingested by small drifting animals called zooplankton that, with phytoplankton, make up the food supply upon which almost all marine organisms are ultimately dependent. In 2013 the research team used bioimaging techniques to document that microplastics could be consumed by a range of zooplankton species (Figure 1). Additionally, laboratory-based feeding rate studies were used to demonstrate that microplastic ingestion decreased food consumption in exposed zooplankton [3.2]. More recently, field studies conducted by PML have confirmed that zooplankton, such as fish larvae, are consuming microplastics in the natural environment [3.3].

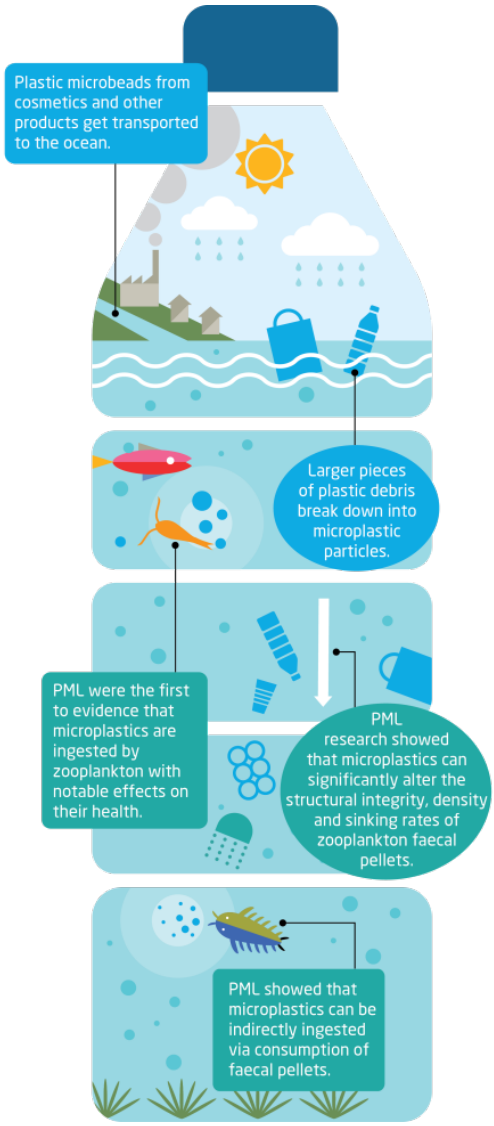
In 2015 PML demonstrated that microplastics can have a significant impact on how small crustaceans called copepods feed, with notable costs to the health of individual animals. Copepods are a globally abundant type of zooplankton that form a key nutritional link between primary producers and consumers further up the food chain. Dr Cole exposed a common copepod species to polystyrene beads representative of the size of microplastics used in personal care products. The exposure resulted in the copepods consuming smaller, less nutritious prey than usual, leading to a significant reduction in the amount of food ingested. Prolonged exposure to microplastics resulted in a 40% reduction in energy consumed by the copepods causing them to produce smaller eggs with reduced hatching success [3.4].

In 2016 the team explored the effects of microplastics egested by zooplankton in their faeces. Zooplankton faecal pellets are an important food source for marine organisms but they also play an instrumental role in the biological pump. This transports particulate organic matter, nutrients,

pollutants and carbon to deeper waters and the seafloor. The PML research team found microplastics can significantly alter the structural integrity, density, and sinking rates of faecal pellets. At average oceanic depths, it was calculated that pellets containing polystyrene microplastics would take 53 days longer to reach the seafloor. These pellets would therefore be more prone to consumption and degradation during their descent compared to faecal pellets devoid of plastic, leading to the reduced transport of organic matter to the seafloor. The research further illustrated that microplastics can be indirectly ingested via consumption of faecal pellets [3.5], highlighting them as a novel vector for incorporation of microplastics into the food web.

Research undertaken at PML has identified that plastic can be transferred through feeding from fish to marine mammals [3.6]. These findings have contributed to growing concern that humans may also be consuming microplastics through the food we eat and highlighted the need for further research on what the implications of microplastics on human health might be.

In 2019 PML's research team went on to reveal the impacts of microplastics of varying shape and size on copepods. Exposure to nylon fibres was shown to cause a 40% decrease in algal ingestion rates and triggered premature moulting in juvenile copepods. The results emphasized that the shape and chemical profile of a microplastic can influence its bioavailability and toxicity [3.7]. Furthermore, PhD student Rachel Coppock identified that different types of plastic can change the density of copepod faecal pellets, either increasing or decreasing their buoyancy and sinking rates. This has potential implications for the carbon cycle and the transport of microplastics and food through the ocean [3.8].



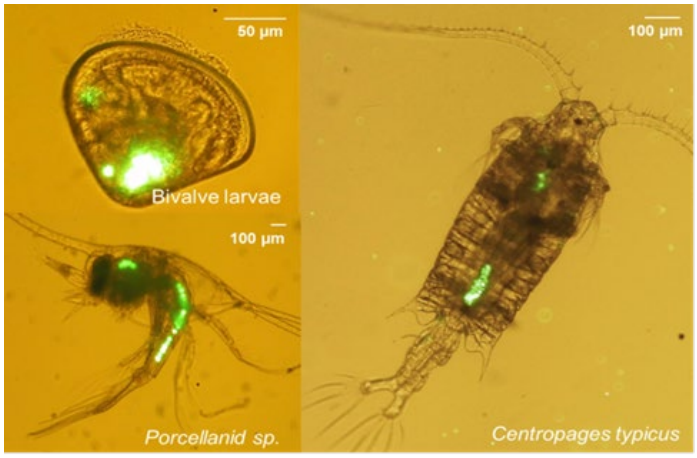


Figure 1. Left: Infographic showing PML's microplastic research (teal boxes) adapted from PML Annual Review 2016. Above right: Zooplankton showing ingested microplastics.

3. References to the underpinning work

PML authors are highlighted in bold type, citation numbers from Web of Science 7 January 2020.

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4. Details of the impact

PML has significantly increased understanding of the impact of microplastics on zooplankton. The team's research has contributed evidence to underpin domestic and international legislation to reduce plastic entering our oceans. Through outreach activities PML has raised awareness of the scope of the plastic problem and helped to change public perceptions and behaviour.

Shaping national policy

Informed by PML research, the UK government passed legislation in 2016 to ban the manufacture of products containing microbeads, one of the world's most stringent bans. This ensures that manufacturers of cosmetics and personal care products sold in the UK are no longer able to add tiny pieces of plastic to rinse-off products such as face scrubs, toothpastes and shower gels.

PML contributed to the evidence base that underpinned the ban. Specific references were made to PML's research, with Dr Cole as the most cited researcher in the Parliamentary Office of Science Technology's POSTNote [5.1]. This research provided the only evidence relating to impacts on zooplankton. Dr Lindeque presented to members of the Houses of Commons and Lords, including Select Committee members and the Parliamentary and Scientific Committee, in the lead up to the ban. In addition, 6 PML scientists and students provided written evidence to the Environmental Audit Committee inquiry on the environmental impact of microplastics. The POSTNote and PML's written submission were used as evidence in the Committee's report that put forward the recommendation to ban the use of plastic microbeads, which was enacted by the UK government.

The ban came into effect in January 2018, which has led to a reduction of 4,000 tonnes of plastic entering the ocean every year [5.2]. This equates to the protection of marine natural capital of at least USD13,200,000 (05-2019) each year, based on conservative calculations of the cost each tonne of marine plastic debris can have on marine ecosystem goods and services [3.1].

The ban is a key first step in making sure UK government policy is tackling plastic pollution in the marine environment. Defra are continuing to address and expand on this issue on behalf of the government through a Marine Plastic Pollution Evidence Review. PML has been integral to this process: the microplastics team co-authored 3 of 6 rapid-reviews requested by Defra; Drs Lindeque, Beaumont and Cole presented at the review workshop in March 2019; and Dr Lindeque was the co-scientific lead on the final report that she presented to DEFRA in October 2019. The results of the evidence review and workshop will be used in Defra policy work to help direct future funding and to identify the most harmful types of litter [5.3].

"*As the first researchers to identify the impact of plastic on zooplankton, PML have been instrumental in raising awareness of the breadth of this issue and bringing it to the fore of political awareness. PML produced 3 comprehensive reports for the government's Marine Plastic Pollution Evidence Review that provided important information for our approach to addressing marine plastic pollution*" Department for Environment Food and Rural Affairs [5.4].

Global influence

Leading on from the UK microbead ban, PML's research has been used as evidence for legislation to ban microbeads in Canada [5.5], New Zealand [5.6], South Africa [5.7] and Sweden [5.8]. For example, PML's research is referenced in the Canadian Environment Agency's, *Microbeads, a science summary* which called for microbeads to be classified as a toxin under environmental protection law [5.5] and ultimately led to a ban that came into effect on 1 January 2018.

The EU is considering the restriction of microplastics in products which are intentionally added during manufacture and are likely to be released to the environment. In 2018 it commissioned the European Chemicals Agency to review the available scientific evidence and to produce a proposal for the restriction. Three of Dr Cole's papers on the impact of microplastics on zooplankton are cited in the proposal. The restriction report features a table of the 25 most influential articles on the (eco)toxicity of microplastics [5.9] in which Dr Cole's papers feature 2nd and 9th.

The proposed EU-wide ban will be voted on in 2020 and, if adopted, will mean restrictions on microplastic use from 2022 for all 28 member states. The report states that only Union-wide measures will curb microplastic emissions effectively and ensure the free movement of goods within the Union. The European ban aims to cut 90% of microplastic pollution, amounting to 400,000 tonnes of microplastics over the 20 year period following its entry into force [5.9].

PML's research has also featured in reports from intergovernmental organisations that aim to address this global problem. These include the United Nations and the World Health Organisation. The UN's Environment Programme produced the report *Marine plastic debris and microplastics – Global lessons and research to inspire action and guide policy change,* which drew upon and made reference to PML's papers. The report is the supporting evidence for 3 UN resolutions on marine litter and microplastics [5.10] that call for Member States to create action plans to tackle plastic pollution.

Raising awareness and changing behaviour

The first ever footage of zooplankton eating microplastic was filmed at PML in 2014, which featured in a short film that won the Atkins CIWEM Environmental Film of the Year. The footage received global media attention featuring on websites including the New Scientist and Mail Online. It was aired on prime-time programmes including BBC and ITV local and national news and BBC's The OneShow and Inside Out, with a potential combined reach of over 20,000,000 people [5.11].

In 2017 the BBC filmed zooplankton eating plastic at PML, which featured in the final episode of Blue Planet II and the accompanying book. The episode was watched by 12,000,000 viewers in the UK, broadcast internationally on BBC Earth channel and sold to more than 30 countries. The episode informed a global audience of the dangers of plastic waste, which helped to trigger global debate and a shift in attitudes. *"The 'Blue Planet effect' has been cited in many actions by government and businesses"* [5.2].

PML's work on marine plastics has featured in over 20 print and online newspaper articles, with a total readership in excess of 100,000,000 people [5.11]. Dr Lindeque and Dr Cole have been interviewed for several documentaries including *Eating our way to extinction* and Al Jazeera's *Earthwise* programme. Dr Lindeque was recently an expert panellist on the Royal Institution debate on *Marine plastics: is it too late to save our oceans?*

PML has contributed to educational programmes such as EncounterEdu.com, creating a resource pack for teaching 14–16 year olds. PML was the Science Partner for the educational unit, *Plankton, Plastics and Poo,* which has been downloaded 6,387 times by teachers, educating at least 236,000 students.

At the grass roots level PML is active in the community; visiting schools and universities, presenting at exhibitions and collaborating in art projects. This has directly led to changes in behaviour with schools feeding back that they have implemented plastic reduction policies and targets. *"Dr Lindeque's visit inspired our students to launch a recycling scheme, raise awareness within the school and local community and find ways to reduce plastic use."* Kingsbridge Community College [5.12].

PML's microplastic research, alongside work from the Universities of Exeter and Plymouth, won the prestigious NERC societal impact award and the overall winners award in December 2018. The accolades recognised the efforts of the 3 organisations to bring the causes and effects of plastic pollution to the attention of policy makers, industry and the general public globally. In November 2019 Dr Lindeque received the Highly Cited Researcher award from Web of Science for her work in the field of Environment and Ecology [5.13].

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Centre: **Plymouth Marine Laboratory (PML)**

Title of case study: **Ocean acidification: ensuring national and international decision makers understand this global threat to set targets and inform international agreements**

1. Summary of the impact

The ocean is becoming more acidic as a result of carbon dioxide emitted from human activities, with serious consequences for marine life. Based on an extensive understanding of changing ocean chemistry, PML has investigated how marine life is responding. This knowledge has been used to demonstrate the damaging effects of ocean acidification (OA) under different future scenarios to inform policy makers. PML has been pivotal in raising awareness and inspiring action on OA at the highest political levels. This influence has culminated in the significant recognition of the ocean in the Paris Agreement, a global accord to address climate change, and the development of a UN Sustainable Development Goal target on OA (SDG14.3). PML coordinates the northeast Atlantic OA monitoring network, which contributes to the delivery of the UK's obligations under this target.

2. Underpinning research

At least one-quarter of carbon dioxide (CO_2) released by burning fossil fuels has dissolved into the ocean, decreasing the pH of seawater. In the past 200 years the ocean has become 30% more acidic [3.1], an unprecedented rate of change which does not allow enough time for all marine life to adapt. The resultant loss in biodiversity will affect fisheries and aquaculture, threatening food security for millions of people, tourism and other marine-related economies.

Since 2003, when ocean acidification (OA) was first identified as a concern, PML has significantly developed scientific thinking with over 189 papers published, receiving over 7000 citations from 4474 separate articles [3.2]. Through laboratory and field experiments, observations and ecosystem modelling PML has investigated the impacts of OA on marine organisms and their ecosystems. An early key finding was that calcification by animals could be increased in response to OA, contrary to popular belief that rates would decrease [3.3]. PML demonstrated that some organisms can increase their metabolism and rate of calcification in response to greater acidity, but at the cost of muscle wastage. This means such adaptations are unlikely to be sustainable in the long term. The research was conducted as part of a PhD project at PML under the supervision of Dr Steve Widdicombe (lead) and Dr John Spicer (University of Plymouth). These findings changed understanding of how organisms respond to OA and led to a "whole organism approach" using models to simulate the consequences of changing acidity, by considering an organism's energy requirements over its entire lifecycle.

PML's Dr Widdicombe (Professor from 2014), led the first UK research project on the environmental risks of high CO_2, *Implication for the Marine Environment of* CO_2 (IMCO2). IMCO2 created a modelling capacity for exploring the effects of high CO_2 on UK shelf waters; demonstrated that decreasing seawater pH could lead to a gradual decrease in benthic diversity and identified the more vulnerable organism types; and raised awareness of OA ensuring it was considered alongside climate change as a threat to the future health of our planet [3.4].

PML has measured OA parameters since 2009 utilising its sampling platforms; the Atlantic Meridional Transect (AMT) and the Western Channel Observatory (WCO). Spanning the length of the Atlantic, the annual AMT research cruise provides basin-scale observations, whilst WCO provides weekly localised sampling. Together, these provide the longest running and most comprehensive dataset of carbonate chemistry in the UK, which is vital to quantify long-term changes in OA. This freely available data underpins much of our understanding of the interplay between the chemistry of the ocean and biological processes. This expertise has led to PML coordinating the NE Atlantic regional hub of the Global Ocean Acidification Observing Network (GOA-ON) and involvement in the OSPAR Intersessional Correspondence Group on OA.

PML evidence on the impacts of OA contributed to increased intergovernmental concern. In 2008 the first international research effort on OA, the European Project on Ocean Acidification (EPOCA), was funded by the EU. Dr Carol Turley was a member of the Executive Board and leader of one of the four themes. Dr Turley also led the development and writing of the Science Plan for the 5-year

UK Ocean Acidification Research Programme (UKOA), which was funded (GBP12,000,000) by NERC, the Department for Environment, Food and Rural Affairs (Defra) and the Department of Energy and Climate Change (DECC) in 2010. PML led 3 of the 6 UKOA consortia and made key contributions to the others, producing the first long-term multispecies and ecosystem studies on the impacts of OA across Europe, North America and the Arctic. The Benthic Consortium, led by Dr Widdicombe, developed a novel experimental system to replicate the environment under different OA conditions. This advanced investigations into the impacts of OA on seafloor organisms [3.5].

PML's research has increased our capability to generate model projections that aid understanding of what marine systems may look like in the future. By modelling climate responses and OA at regional scales the UKOA Modelling Consortium demonstrated that the impacts of warming and acidification are strongly coupled. Led by Jerry Blackford, the group showed that this coupling effect delivers a highly complex and variable response that has significant consequences for adaption and management strategies. Understanding these effects enables policy makers to make informed decisions when setting targets [3.6].

Many of PML's researchers, from multiple disciplines, have contributed to OA research over the last two decades. The key co-ordinators of this work have been Dr Turley (Microbial Ecologist at PML since 1990), Dr Widdicombe (Marine Ecologist at PML since 1991) and Mr Blackford (Mathematical Modeller at PML since 1991).

3. References to the underpinning work

PML authors in bold type, citations from Web of Science 7 January 2020 unless otherwise stated

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4. Details of the impact

Informing government bodies of the risks of OA

PML led a key Defra report in 2004 on elevated CO_2 in the marine environment, which highlighted the potentially devastating consequences for marine life. Dr Turley contributed to the Royal Society working group on OA, which authored a seminal report on OA [3.1] and culminated in the recommendation that "*action needs to be taken now to reduce global emissions of CO_2 from human activities to the atmosphere to avoid the risk of irreversible damage*" [3.1]. The Royal Society report "*raised the profile of ocean acidification with politicians and the public alike*" [5.1] and formed the basis of the 2009 InterAcademy Panel statement on OA, which was endorsed by 105 national academies worldwide. This was the first time that these bodies officially recognised the threat of OA and called for action.

Ensuring OA is included in climate change assessments informing international targets

In 2005, Dr Turley ensured OA was included for the first time in an Intergovernmental Panel on Climate Change (IPCC) Assessment Report. She joined the Panel as a Lead Author of the

Ecosystems chapter and drove the inclusion of the latest OA research findings in its 4th Assessment Report (AR4). IPCC is recognised globally as the most authoritative scientific and technical voice on climate change research. Its reports have the agreement of leading climate scientists and consensus from participating governments.

Dr Turley continued as a Review Editor for the 5th IPCC Assessment Report (AR5) and ensured an increased marine prominence with two separate chapters on the ocean. AR5 was recognised as a *critical scientific input into the UNFCCC's Paris Agreement in 2015* [5.2]. PML's input was central to OA being recognised as a major climate stressor within the IPCC as evidenced by its latest Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) where Dr Turley was once again Review Editor.

Ensuring the 'ocean' is included in the landmark UN Paris Agreement

PML has participated in every United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) since 2009. At that point the ocean received very little attention and OA was not considered. Dr Turley led an awareness raising campaign at the 2009 UN event. PML went on to lead and organise similar campaigns at every subsequent COP and other landmark meetings, including the Rio+20 Earth Summit. These activities ensured the latest research findings were communicated to delegates from across the world.

At COP21 in 2015 Dr Turley led an EU side event, was a panel member on 5 side events, co-organised Oceans Day and gave media interviews. Through a series of conversations and exchanges she was pivotal to informing political negotiators of the role of the ocean in the climate system. The landmark Paris Agreement was negotiated at this meeting, with every word debated and scrutinised to ensure agreement from all parties. On hearing that a draft agreement did not include any mention of the ocean, Dr Turley used her high profile position to galvanise action from other delegates, targeting national negotiators to emphasise that the ocean has to be considered in any action to manage and mitigate climate change. The final Paris Agreement stated '*the importance of ensuring the integrity of all ecosystems, **including oceans**, and the protection of biodiversity …when taking action to address climate change.'* Dr Turley is widely acknowledged by her peers for being instrumental in ensuring the ocean was included in this global accord.

"The product of [Dr Turley's] collaborative activities was the inclusion of ocean ecosystems in the Paris Agreement, the development of an ocean acidification goal in the UN SDGs and in-depth recognition of the issue by high level negotiators worldwide" US National Oceanic and Atmospheric Administration [5.3].

PML continues to be very active in COPs and has worked closely with numerous parties, including Government Departments, to organise science to policy events to bring the latest scientific understanding to climate negotiators and other delegates. PML advised Defra on the UK government's ocean approach to COP24 (2018) and COP25 (2019) and worked with them to arrange science events and displays at the UK Pavilion at COP25. PML researchers presented, led and partnered in more than 10 important ocean-focused events and contributed to 5 major reports that were presented at the event. These activities contributed to a greater acceptance of the importance of the ocean in climate change in the *COP25 Outcome Document*, which includes unprecedented action for better integration of ocean and coastal ecosystems in future COPs.

"Dr Turley first told the story of the up-to-that-point unknown effects of ocean acidification on marine species and processes at COP 2009, making the delegates and other decision makers aware of these very troublesome effects for the very first time. Her extraordinary influence has been key to each subsequent COP and most recently was crucial to getting a greater acknowledgement of the importance of the ocean in the COP25 outcome document in 2019". President Global Ocean Forum [5.4].

"*PML is a trusted partner, providing scientific expertise and advice to support Defra's engagement at the UNFCCC COP. PML's presence at COP25 alongside Defra helped to raise the profile of the ocean in climate change, and helped to ensure a greater acknowledgement of the importance of the ocean in the conference's outcome document. PML is recognised as a world leader in climate research, monitoring and action, and supported the UK Government to showcase and engage with international partners on climate change and ocean change issues at this important event".* Chief Scientific Advisor, Defra [5.5].

Informing UN resolutions and voluntary commitments to deliver action under the SDGs

In 2017 PML played a key role in the high-level UN Conference to Support the Implementation of Sustainable Development Goal (SDG)14 – Life Below Water. Dr Turley was a member of the Informal Preparatory Working Group for SDG14.3, focused on minimising the impacts of OA. The conference included plenary meetings and partnership dialogues. Dr Turley was an invited science representative as one of 4 panellists on the *Minimizing and addressing OA Partnership Dialogue*. Dr Turley presented on OA, directly influencing the UN Secretary General's Special Envoy for the Ocean who requested her slides to inform his speeches.

1,395 voluntary commitments for the implementation of SDG14 were registered during the conference, with approximately USD25,400,000 (06-2017) in monetary resources pledged. 236 of these related to OA, either as the main component, or as part of a broader range of management and conservation actions [5.6].

Dr Turley contributed to writing the session summary from the Partnership Dialogue that fed into the final conference report, *Our ocean, our future: call for action*, which was agreed by all parties to the conference. The report, aimed at supporting the implementation of SDG14, was officially endorsed by the UN on 6 July 2017 [5.7]. A further UN resolution on SDG14 (9 May 2019) formally recognised *'the important contributions of the partnership dialogues and voluntary commitments made in the context of the Conference'* [5.8].

"*After listening to Carol Turley speak about ocean acidification in the Partnership Dialogue at the UN Ocean Conference in New York in 2017, the full seriousness of the issue was brought home to me. In the ensuing years, I have been pleased to lend my support to events on the topic that she has organised at the COPs of UNFCCC. She does a great job of bringing the science of ocean acidification to policy makers, making them more aware of this key reason for greater ambition in reducing CO_2 emissions and meeting the Paris Agreement."* UN Secretary General's Special Envoy for the Ocean [5.9].

In 2011 Dr Turley was recognised for her services to science and awarded an OBE in the New Year's Honours list, her work on OA was a key element of the nomination. "*In my view, Dr Turley has achieved higher policy impact on behalf of NERC than any other individual during the past 5 years (if not 50 years)*", University of East Anglia [5.10].

Ensuring the delivery of OA monitoring data to meet SDG14.3

As part of the delivery of SDG14.3 member states are required to provide pH measurements to be used as an indicator for OA (target 14.3.1). PML co-ordinates OA monitoring efforts for the northeast Atlantic region, facilitating 12 countries to deliver their commitments towards SDG14.3. PML coordinates the NE Atlantic hub, part of the Global Ocean Acidification Observing Network (GOA-ON). The hub ensures a common methodology for recording measurements, enabling submission to the UN through National Data Centres, and cataloguing of the data on a central global portal that maps effort and identifies gaps.

As well as coordinating the NE Atlantic hub, 1 of 7 global regions, PML was a founding member of this global network. Through involvement in international workshops in 2012, PML was instrumental in the development of GOA-ON, contributing to its visions and goals. Dr Findlay is currently the only UK representative on the network's Executive Council and Dr Widdicombe represents GOA-ON on OSPAR's Intersessional Correspondence Group on OA.

GOA-ON co-ordinates international action to expand OA observations, addresses capacity gaps, connects scientists, and disseminates the latest OA findings. The network helped to ensure pH was recognised by the UN as an effective indicator for SDG14.3 (SDG14.3.1) and produced the methodology for this measurement. As such the network has underpinned the upgrade of the indicator from a Tier 3 to a Tier 2, demonstrating that the '*Indicator is conceptually clear, has an internationally established methodology and standards'*. A central goal of GOA-ON is to ensure that data are regularly produced by at least 50% of countries so that the indicator can be upgraded to Tier 1 by the UN. This is being initiated by PML through implementation of the methodology across the NE Atlantic hub.

"*PML have been key partners in the Global Ocean Acidification Observing Network since its inception in 2012 and are leading and setting-up the NE Atlantic Hub, crucially delivering on*

SDG14.3 and ensuring the implementation of GOA-ON's methodology across the region." Co-chair GOA-ON Executive Council [5.11].

In 2018 Dr Widdicombe was appointed by Defra to contribute to an OA group to review the current monitoring of OA at the UK and global scale to ensure the UK demonstrates global leadership. Its recommendations to Defra included utilising existing platforms and technology to effectively monitor OA and identifying where additional resources were needed. Dr Widdicombe was instrumental in integrating GOA-ON methodology and approaches as well as PML's long-term monitoring capabilities into the group's report and recommendations. He provided the group with long-term data plots from WCO and AMT to inform discussion, emphasising the value of PML's existing capabilities and the need to build on these to meet international monitoring requirements.

Implementation of the report's recommendations resulted in Defra funding PML to co-ordinate the NE Atlantic Hub, providing the UK's contribution to GOA-ON. The remaining recommendations are with the UK government and will inform the planned UK OA Action Plan, which PML has been commissioned by Defra to produce in 2020.

"PML is a trusted partner to support this [GOA-ON] co-ordination of international monitoring efforts which contribute to the UK obligations under the SDG14.3 to minimise and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels... The joining up of international expertise via the NE Atlantic Ocean Acidification Hub will enhance our knowledge of the environmental change, which for Defra is vital to underpin policies." Head of Ocean Climate Policy & Marine Evidence, Defra [5.12].

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ENVIRONMENT STATEMENT: PLYMOUTH MARINE LABORATORY (PML)

SECTION A: NARRATIVE

To note PML has not been subject to a previous NERC Centre REF exercise.

Context, Mission and Strategy

For over 40 years PML has delivered the pioneering research needed for sustaining the global ocean, its ecosystems and resources for the benefit of society. PML delivers and applies the best available science, and develops new techniques and approaches to deliver independent, impartial, policy relevant research and advice on the marine environment.

PML's mission is to undertake cutting-edge, interdisciplinary research in the sunlit ocean in anticipation of growing societal needs and to promote stewardship of marine ecosystems (from PML Strategy *Listen to the Ocean* 2015-2019).

PML's charitable objects are to carry out research in environmental science and technology, including marine and estuarine environmental science and technology, and disseminate results of such research, and data and ideas generated, in the course of or in connection with such research for the benefit of the public; to advance public education in the principles and practice of such science and technology.

Governance & Structure

Since April 2002, when it was released from NERC ownership, PML has operated as an independent company limited by guarantee[1] with charitable status[2]. PML is governed by a Board of Trustees, who are required to comply with both charity and company law and whose remit it is to ensure long-term sustainability of the organisation.

The Board is committed to ensuring best practice in governance, and has signed up to, and implements, the seven principles of the Charity Governance Code (2017)[3]. A Statement of Delegated Authority is in place between the PML Board of Trustees and PML Executive which defines clearly the responsibilities of both bodies.

PML's wholly-owned commercial trading subsidiary – PML Applications Ltd – was set up in 2002, and facilitates the application of research from PML and undertakes commercial work that PML cannot do because of its charitable status. The relationship between PML and its subsidiary is clearly laid out, and a clear charging mechanism exists between the companies for use of staff time and resources. PML Applications also gift aids profits made within a financial year to PML. Together PML and PML Applications Ltd are known as the PML Group.

Since 1 October 2019 PML has had a new Chief Executive, Prof. Icarus Allen, who is also Chief Executive of PML Applications Ltd, which enables positive interactions between the two organisations.

Organisation

Day-to-day responsibility for the operation of PML lies with the Chief Executive, who chairs the Senior Management Team (SMT) - Figure 1. The SMT, which has specific Terms of Reference,

[1] company number 4178503
[2] charity number 1091222
[3] https://www.charitygovernancecode.org/en/front-page

leads on the direction and overall management of PML, focusing at a strategic level on the business, science and operational services.

The Science Team (ST) is a delegated body of the SMT responsible for the leadership and implementation of PML's science strategy, determining the deployment and use of scientific staff and financial resources and developing strategic scientific collaborations, partnerships and networks internally and externally.

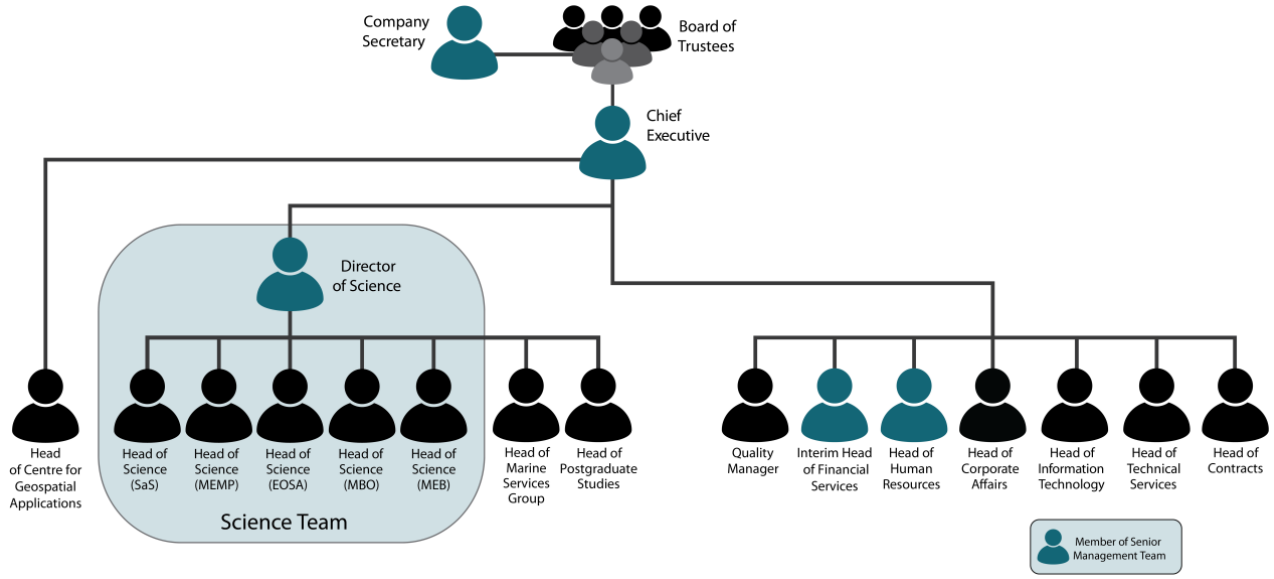
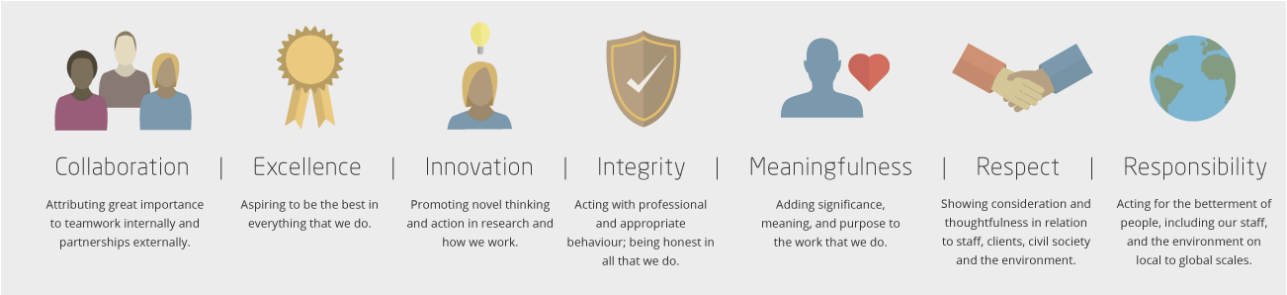


Figure 1: Our organisational structure.

Our Core Values

At PML Group level a core set of values has been developed in conjunction with our staff and students (see below). These values guide us in defining our strategy, aims and objectives and are central to what we do.



Size

Below are figures for both people and finances, denoting the size of the PML Group.

People

Over the six year period since January 2013, the average number of Full-Time Equivalent (FTE) employees was 146; currently 150 FTEs. This size of organisation has proved optimal for interdisciplinary working. The current ratio of science to operations staff is 74%/26%.

In addition, PML hosts annually a large visitor community, comprising students (undergraduates, MSc, PhD), Fellows and other visiting researchers from around the world. Over the same period, the average number of "total visitors" was 77 per annum.

PML Applications Ltd, employs a small number of staff (it also uses, and pays for, staff resources from PML). The average number of FTEs directly employed by PML Applications over the six year period was 6. The current number of FTEs in PML Applications stands at 8, with the company investing in further resource as it grows.

Strategy

The PML strategies *Science for Society* (2010–2014) *and Listen to the Ocean* (2015–2019) identified three strategic aims

- **Quality**: To undertake research in environmental science and technology that is of outstanding quality and relevance for the benefit of society.
- **Competitiveness:** To conduct research in a focused, effective and cost-effective manner in acknowledgement of the contributions received from public, private and charitable sources of funding.
- **Responsibility:** To behave responsibly towards staff, society and the environment. To advance science and disseminate the results of PML's research, data and ideas as widely as possible in order to maximise our impact on addressing societal challenges, enhancing public wellbeing and providing knowledge and education.

A short film on PML can be found on the homepage of our website at https://www.pml.ac.uk/ giving an overview of PML's aims.

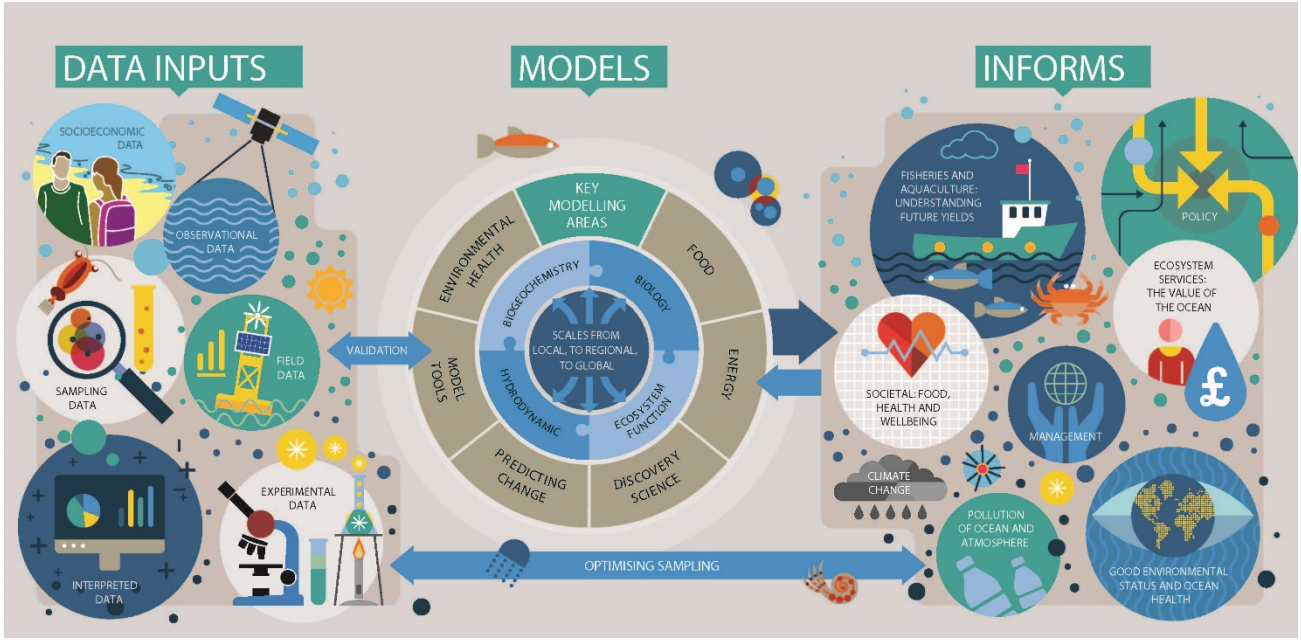


Figure 2: How PML science works.

An interdisciplinary approach to tackling complex societal challenges is a key strength and feature of PML (Figure 2). PML brings together researchers from different scientific disciplines, to work collaboratively in order to create and apply observations and models alongside new knowledge and thinking to address societal challenges.

Our brochure *Science for Sustainable Ocean Development*, providing an overview of PML research is available at https://www.pml.ac.uk/News_and_media/Corporate_publications

Achievement of Strategic Aims – Research & Impact (past)

The research priorities and high level delivery of PML's science areas are:

Sea & Society: Integration of evidence from natural and social sciences in order to understand the consequences and benefits of the interactions between society and the marine environment. To improve the outcomes and benefits, and to support sustainable and responsible ocean stewardship:

Examples of delivery:

- Methodologies for the economic and social valuation of natural capital (Beaumont 2014 *et al*.).
- Development of socio economic strategies for improving the resilience of communities and marine ecosystems to changes anticipated as a result of climate change.
- Demonstration that coastal locations are more psychologically beneficial to individuals than urban green spaces (Wyles, Hattam & Austen, 2017).
- Holistic approaches that quantify the impact on ecosystem services in the presence of marine plastic (Beaumont *et al.,* 2019).

Earth Observation Science & Applications: Use of Earth Observation (EO) data to conduct fundamental and applied research on physical and ecological processes in oceanic, coastal and inland waters. Support interdisciplinary science and operational monitoring, nationally and globally.

Examples of delivery:

- NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) offers a range of services including: systematic acquisition and processing of data from a number of satellites, and near-real time support.
- Climate Quality Ocean colour data products, algorithm development and validation (Brewin *et al*., 2015) for the ESA sentinel satellites including the collection of high quality *in-situ* data.
- Developing new approaches for monitoring water quality (freshwater and marine), marine litter and illegal fishing.
- Combining data from bio-argo and satellites to demonstrate that the seasonal mixed-layer pump is an important source of organic carbon for the mesopelagic zone (Dall'Olmo *et al*., 2016).
- Assessment of the impacts of large-scale climate patterns on plankton distribution (Sathyendranath, 2017).

Marine Biogeochemistry & Ocean Observations: Quantification of key physical and biogeochemical processes in the surface ocean and coastal seas, together with exchange mechanisms between ocean and atmosphere. Understand and predict the functioning of the global Earth system in a changing world.

Examples of delivery:

- Air-sea (ice) flux measurements of climatically active gases using Eddy Covariance and evaluation of air-sea flux parameterisations (Blomquist *et al*., 2017).
- Atmospheric composition measurements (O_3, CH_4, CO, aerosols) at the Penlee Point Atmospheric Observatory (Yang, 2019).

- Maintenance of the buoy infrastructure and biogeochemical time-series at the Western Channel Observatory (WCO)[4].
- Delivery of biological, chemical and physical observations on the annual Atlantic Meridional Transect (AMT)[5] cruise.
- Field observations to quantify and understand the carbon production and loss processes (Pabortsava *et al*., 2017; Kiditis *et al*., 2019) and sources and sinks of biogenic nitrogen (e.g. Ovadnevaite *et al*., 2017) in the marine environment.

Marine Ecology & Biodiversity: Explore the fundamental ecological processes and interactions that support biologically diverse and productive marine ecosystems. To understand how and why marine ecosystems change through time and space, and what drives their resilience or sensitivity to environmental stress.

Examples of delivery:

- Maintain long-term time series of plankton and benthos observations at the Western Channel Observatory (WCO).
- Organism and ecosystem response and resilience to climatic (Beaugrand *et al*., 2019) and anthropogenic stressors such as microplastics (Cole *et al*., 2013), ocean acidification (Russel *et al*., 2015; Vargas *et al*., 2017; Widdicombe, 2017) and urban light (Davis & Smyth, 2018).
- Demonstrate the significance of zooplankton in mediating biogeochemical process and carbon export (Atkinson, 2017; 2019).
- Querios *et al*. (2019) demonstrated the previously ignored significance of offshore sediments for the overall carbon sequestration potential in the coastal ocean.

Marine Ecosystem Models & Predictions: Develop and maintain world-class, scalable modelling frameworks that assess the structure, function and dynamics of the marine systems, from estuaries to shelf seas and the global ocean. Support their use for the management of marine systems. Achieve impact on policy and regulatory decision making.

Examples of delivery:

- Led a national team (NOC, Cefas, and UK Met Office [UKMO]) to improve and maintain the European Regional Sea Ecosystem Model (ERSEM)[6] as a community model.
- ERSEM is a component of the UKMO operational UK shelf seas model.
- Modelling ecosystem response to climate change (Chust *et al*., 2014), ocean acidification (Calosi *et al*., 2017) and fisheries (Barange *et al*., 2014).
- Biogeochemical process models and evaluation tools.
- Biogeochemical data assimilation methods and reanalysis simulations (Ciavatta *et al*., 2016).

Centre for Geospatial Applications (CGA): To deliver operational products in Earth observation and visualisation. CGA straddles both PML and PML Applications Ltd and was set up in April 2017 to take on the service delivery and the more commercial aspects of Earth observation research, thus bringing these activities to the market using PML Applications as the vehicle.

[4] http://www.westernchannelobservatory.org.uk/
[5] http://www.amt-uk.org
[6] https://pml.ac.uk/Modelling_at_PML/Models/ERSEM

Examples of delivery:

- Delivery of near Real Time Ocean Colour data for COPERNICUS,
- Development of an oil response system for the Malaysian government and
- Training in the use of Earth observation data for EUMETSAT.

Publications

PML published 1168 papers in ISI journals during the assessment period. Collectively, these papers have been cited over 20000 times and have achieved an H index of 60, with 50 of these papers being identified as highly cited in the field[7]. There were 3 papers in Nature, 1 in Science, another 44 other in Nature Journals[8] and 6 in PNAS.

Delivering Impact

PML delivers a diverse range of policy, economic and societal impacts embracing its diverse range of research-related knowledge and skills to benefit individuals, organisations and nations. The demonstration of impact is a two stage process:

Pathways to Impact: Impact specialists within the Corporate Affairs team support researchers during grant preparation to develop the pathways to impact, identifying potential economic, societal and policy impact outcomes. These outcomes are delivered using a variety of approaches including communications, stakeholder mapping and engagement, marketing, and protecting Intellectual Property. Wherever possible, projects are co-developed with stakeholders from the start to ensure the research activities are strongly matched to the impact needs, e.g. the Addressing Challenges of Coastal Communities through Ocean Research for Developing Economies (ACCORD) project. The simple provision of information is not a guarantee of impact and PML actively pursues actions that facilitate change in both policy and behaviour. Elements of commercial impact are largely delivered in partnership with PML Applications.

Impact Demonstration: To ensure that pathways to impact are being delivered effectively and that impact activities are achieving their desired outcome it is essential to collect and monitor evidence of impact generation. The 'Altmetric' software tool is used to identify where PML outputs have contributed to a key impact-related activity, such as policy documents, and contributions to patents. Additional metrics, such as personal testimonies from stakeholders, are also collected. A dedicated impact team is in place which works across PML to collect and review this evidence and use it to demonstrate the impact from PML's research. The team identifies potential impact stories and works with the major actors to record the evidence that demonstrates impact and to prepare the impact narratives, tailoring them to a range of stakeholders. A new PML impact strategy is currently under development.

For the purposes of the current REF assessment, PML explored the full range of potential impacts and identified 12 potential examples. Following an intensive period of evidence gathering, the final impact stories were selected using the following criteria as a guide:

- A clear description of the research with relevant references.
- Clear impact well linked to the research.
- Robust evidence corroborating real change.
- Demonstration of multiple impacts, e.g. a national and an international dimension.

[7]Source ISI Web of Science 15th January 2020
[8] Nature Climate Change, Nature Geosciences, Nature Communications, Scientific reports

The following impact stories were selected

- **Ocean acidification:** PML has been pivotal in raising awareness and inspiring action on Ocean Acidification at the highest political levels, culminating in the recognition of the ocean in the UNFCCC Paris Agreement and the development of a UN Sustainable Development Goal target on OA (SDG14.3).
- **Shaping marine conservation using satellite data**: PML's research informed the designation of 1,884,700ha of Marine Protected Areas around the UK and 60,133,500ha internationally.
- **Shaping policy and reducing marine plastic pollution**: PML research underpinned UK legislation to ban microplastic beads and as evidence for bans in 4 other countries. It is informing debate in Europe on an EU-wide restriction of intentionally added microplastics.
- **Valuing marine ecosystem benefits and services:** PML research informed government policy and approaches, and the EU Biodiversity Strategy. PML has pioneered a methodology for incorporating natural capital into decision making and enhanced local management strategies.

Details of Future Strategic Aims and Goals for Research and Impact

A new Strategy *Science for a Sustainable Ocean* (2020-2024) is currently under development, led by the Chief Executive, with full engagement of staff. Four strategic priorities have been identified to bring focus to this strategy and guide its delivery:

- **Science excellence and impact:** Strengthening PML as a world leader delivering cutting edge innovative environmental science with impact.
- **Business excellence:** Ensuring PML is an effective, efficient and sustainable business.
- **Social responsibility:** Engaging and supporting our community both internally and externally.
- **Environmental responsibility:** Demonstrating leadership and reducing PML's impact on the environment.

This strategy has been created to set out the organisational direction and applies an adaptive approach to the creation of realistic business objectives. Delivery will be linked to the UN Sustainable Development Goals.

A new *Science to Impact Strategy* is being developed under the leadership of the new Director of Science, Prof. Steve Widdicombe, with full engagement with staff. Science delivery will be structured around established and internationally recognised expertise in PML's science areas and CGA.

Society is facing a number of large, often interconnected, environmental challenges and PML will integrate its science and impact expertise across the organisation to meet these challenges. One of the mechanisms by which PML will do this is through a team of 'Science to Impact Challenge' co-ordinators whose goals are to support the creation and function of cross-disciplinary teams, allowing experts to work effectively together and ideas to cross-pollinate and enhance PML's unique ability to work creatively across science disciplines. Working alongside the existing PML Heads of Science, the team will develop strong relationships with key external stakeholders to ensure a close link between scientific outputs and impact delivery. The five key 'Science to Impact Challenges' that have been identified are:

- Managing and Mitigating Climate Change
- Increasing Environmentally Sustainable Marine Fisheries & Aquaculture

- Delivering Cleaner Seas for People and Nature
- Combatting Biodiversity Loss
- Developing New Technologies and Innovation

These areas will be reviewed regularly to ensure that they remain relevant to stakeholder needs, with new Science to Impact networks being formed, or old ones closed, should the external stakeholder landscape change.

Sharing of Research & Data

Sharing of Research – Open Access: PML makes use of the block grant available from UKRI to publish using gold open access (OA) routes and has a framework in place to manage this fund and report to UKRI. Where gold OA publication is not possible, a green OA route is chosen, i.e. PML research publications are available through the Plymouth Marine Science Electronic Archive (PlyMSEA)[9] which is an open access, searchable repository jointly owned with the MBA. Publications may be available *via* an Accepted Manuscript option, where the journal permits, or in post-print pdf format.

Sharing of Data: PML has in place a Scientific Data Management Policy, which requires adherence to funding body requirements on data management, e.g. data are lodged at recognised Data Centres, such as the British Oceanographic Data Centre. Such data are lodged in a timely manner, in the agreed format, and with all relevant metadata.

Data are also available on specific programme websites. For example, the WCO website – www.westernchannelobservatory.org.uk - provides a vast range of data, from zooplankton to atmospheric aerosol data. Since 1 January 2013 there have been 12,713 downloads of the time series data from the plankton monitoring programme. Similarly for the AMT programme there have been 91,938 downloads of the biological and hydrographic station data collected.

Another example is NEODAAS, where global data such as ocean colour and sea surface temperature, are made available through its website http://www.neodaas.ac.uk.

Similarly, the code for PML's European Regional Seas Ecosystem Model (ERSEM) is available for downloading under a royalty-free licence on PML's website. Since 2013 the total number of people registered to download the ERSEM model code stands at 405.

Culture of Research Integrity

PML operates in accordance with the UKRI Policy and Guidelines on the Governance of Good Research Conduct. Quarterly reporting against these guidelines is provided to PML's Science Team for its review. There have been no instances of misconduct during the assessment period.

Ethics, Legal & Professional Frameworks, Obligations & Standards

Ethics: PML has a process in place to handle ethical approval by way of an agreement with the Research Ethics Committee of the University of Plymouth's Faculty of Health and Human Sciences. This body reviews PML applications that require ethical approval before any such data are collected.

Legal: PML has to operate within charity law. Any research or ancillary activities which fall outside its charitable objects are undertaken by PML's wholly-owned trading subsidiary.

[9] http://plymsea.ac.uk/

PML and PML Applications Ltd comply with the Data Protection Act and General Data Protection regulations in the collection of data, and the processing of data by third parties.

PML also adheres to legal contracts and collaboration agreements for specific competitive research (CR) projects and National Capability (NC) programmes.

Professional Standards: PML and PML Applications Ltd have successfully achieved certification of their business (including research) management systems to ISO9001:2015 in 2017. Recertification was confirmed in January 2020. Both organisations were also awarded certification to ISO45001:2018 Occupational Health and Safety in July 2019. PML Group is working towards the achievement of certification to ISO14001 Environmental Management.

People

PML firmly recognises that its people are instrumental to its success. One of the aims of PML's Strategy (2015-2019), and still applicable, was to position PML as a leading international marine research organisation by recruiting, retaining, developing and motivating highly skilled and committed staff with the intellectual and practical qualities to work flexibly, inspirationally and creatively in an ethical, safe, well-equipped, learning environment.

Staffing Strategy

Reflecting its core values (see p2), PML aims to appoint the very best candidates to the posts it offers. PML's strategy is to offer open-ended appointments, thus enabling scientists to join primarily, but not exclusively, at the post-doctoral level and develop within the organisation. Fixed-term appointments are only offered for specific posts, where the role and/or funding for it, are time-bound.

Each new employee completes a one-year probation period, which includes an initial comprehensive induction on the organisation, and then more detailed training in the role by the line manager and others. Probationary reporting is undertaken at 3 intervals, thus allowing any problems to be addressed at an early stage and corrective action taken. After successful completion of probation, each employee meets with either the Director of Science or Chief Executive as appropriate to discuss their future.

The principal premise, which has operated since PML was released from NERC ownership, is that any new post – whether in science or operations – requires justification, with a case being presented to the Senior Management Team for consideration. For scientific posts, justification is primarily based on the availability of research funding to cover the costs of the post. Hence, apart from strategic investments (see below), any growth in the number of scientists is inherently linked to a growth in funding.

To develop new areas of research PML's strategy is to make internal investment in new staff. For example, the PML Board has designated reserves to support post-doctoral research fellowship programmes, investments having been made in 2013 (4 posts) and again in 2018 (2 posts). The organisation has also self-funded a PML (Lord Kingsland[10]) fellowship on three occasions. Such investments have yielded excellent results with these fellows having published 89 papers since 2013 with a combined H-index of 22.

In November 2019, following advice from the Executive, the Board has decided to invest £200k in an "Education Support Fund". This investment, initially from PML's reserves, will be used to underpin PML's strategy for supporting apprentices, PhD students and postdoctoral research

[10] Named after PML's first Chairman

fellows. PML will also use these funds to lever match funding, e.g. from Doctoral Training Partnerships, research projects, industrial partners and charitable foundations. This fund will help maintain, and enhance, a vibrant learning and development environment within PML.

On the operations' side there have been reductions in staffing in some areas, whilst other areas have experienced growth, or new roles have been created, to meet the evolving needs of the organisation.

The size of PML, in terms of staff numbers, is optimal for effectively delivering interdisciplinary research, whilst avoiding the problems associated with creating silos of activity.

Staff retention rates and new recruits over the period under review are as follows:

Year	Retention Rate	No. of New Recruits
2013/14	92%	18
2014/15	86%	13
2015/16	89%	7
2016/17	88%	10
2017/18	87%	19
2018/19	90%	18

The staffing strategy and development strategies are guided and driven by the strategic initiatives and implementation successes of the research and impact strategy. E.g. the PML Kingsland fellowship programme.

Succession Planning: Succession planning is a key component of PML's staffing strategy. In terms of science staff, there has been an effective strategy of developing and mentoring employees to progress through the organisation, with new staff recruited at junior positions to feed this developmental process. On the operations' side, succession planning for retirements and departures, has usually led to external recruitment to bring new skills and wider experience into the organisation.

Succession planning has been put in place for key roles where there is the potential for future single-point failure, e.g. ship's crew, technical science support roles. To mitigate this risk PML developed an apprenticeship programme in 2016 for which it has also attracted external funding from two charitable foundations (Lloyd's Register Foundation and the King Baudouin Foundation, Belgium), as well as a private donation. To date, three science-based apprentices completed their apprenticeships, and been engaged as open-ended employees. One won the South Devon College Science Apprentice of the Year (2018). A fourth apprentice is now in place, training with the ship's crew. An Apprenticeship Co-ordinator works closely with staff supervising the apprentices, and also with the relevant colleges and training providers.

Staff Development

PML is committed to staff personal and professional development, which encompasses a wide range of elements, including promotion opportunities, formal training, mentoring and learning from the work of internal and external colleagues through a regular seminar series.

PML has a single appraisal (Career Management Review - CMR) system applicable to all employees. The CMR process includes development of a Forward Job Plan and an Individual Development Plan so that the individual and their manager can identify specific training and development needs. The CMR process includes a section on personal development which informs the annual staff development programme managed by our Human Resources Team.

The career development element of the CMR was strengthened in preparation for our Athena SWAN application. Results from a recent staff survey demonstrate the success of this change with more positive responses received to questions on i) provision of advice on career development, ii) feeling supported in career development, and iii) being encouraged to undertake personal development.

The CMR is currently under review to ensure it remains fit for purpose in meeting the needs of both individuals and the organisation.

PML operates a merit promotion scheme for its scientific staff to enable progression through the grades. This is a self-nomination process, with a two-stage review by a paperboard and then by the Merit Promotion Panel. Since 2013 there have been 32 scientists promoted. Of these 47% have been male and 53% female scientists. At the more senior levels (Grade Senior Scientist and above) 44% have been male and 56% female.

On the operations' side PML introduced a job evaluation scheme in 2016 to replace merit promotion. This scheme allows for a job role to be regraded following an evaluation process. Since 2016, 7 operational staff roles have been regraded.

Staff development is also encouraged through organisational level training courses, e.g. health and safety related, to more bespoke training such as the Challenge of Scientific Leadership (attended by 43 employees since 2013) and the Emerging Leaders Programme.

External Training: The table below shows the amount invested in external training activities, provided centrally through HR, or through the areas of science or operational groups. The amount spent annually directly on training as a proportion of the overall payroll costs is equal to or exceeds 0.5%, with the exception of the year 2014/15. This reflects the financial challenges facing PML in that period and the necessity to cut costs.

Year	Training spend (HR)	Training spend in science / ops area	Total spent on training	% of paybill spent on training
2013/14	£18,349	£17,235	£35,584	0.58
2014/15	£2,811	£4,319	£7,130	0.11
2015/16	£25,368	£6,478	£31,846	0.52
2016/17	£20,498	£11,204	£31,702	0.52
2017/18	£36,558	£11,129	£47,687	0.80
2018/19	£26,071	£20,440	£46,511	0.73

In-house Training: In addition to the externally funded courses mentioned above, PML provides in-house training, including a compulsory induction, introduction to CMR for reviewers and reviewees, identifying and measuring impact (of research), media skills, developing personal resilience, merit promotion preparation, finance, mental health awareness, and information technology.

PML regularly runs short health and safety briefing sessions throughout the year, covering topics from risk assessments, COSHH and chemical storage. Some sessions require mandatory attendance and others are well attended.

PML has successfully implemented an in-house mentor programme, providing support and guidance from trained volunteer mentors to support colleagues in their personal development and career enhancement.

Future Training Plan: We are currently developing an essential leadership development programme as part of a toolkit for new leaders, including PIs, which will be a requirement for all employees expected to manage or supervise other employees or students.

We have also commissioned an external consultant to work with us on developing Unconscious Bias training for all employees, which will be piloted with our Senior Management Team in February 2020.

Wider Development Opportunities: These include:

- A regular (weekly) seminar series where external or internal speakers give presentations on their research topics.
- Involvement in working groups or committees which are not specifically related to a research activity, e.g. the Official Development Assistance Steering Group, Athena Swan Committee.
- The recent refurbishment programme, which through its bottom-up approach enabled staff at all grades to contribute to the designs of laboratories and facilities.
- Staff membership of external bodies, e.g. national and international committees reflecting their specialism.
- PML encourages, recognises and rewards research talent at all career stages. PML supports Early Career Researchers (ECRs) to develop networks of peers, and provides training including workshops on mentoring, grant and paper writing and occasionally one-to-one coaching.
- Flexible working polices allow staff to request sabbaticals and leave of absence.
- PML allows study leave for courses that are relevant to PML. For example, study leave was granted to a PML Communication Officer to undertake an MSc in Science Communication.

Connecting Research and Industry: The primary vehicle to stimulate and facilitate exchanges between PML researchers and business/industry is PML Applications Ltd, since all their clients are commercial companies, including a number of global and blue-chip companies. PML staff have the opportunity to work on commercial contracts within PML Applications and thus interact with industry.

PML is also involved with various initiatives locally and nationally, which enable interaction with business and industry. These include:

- The European Regional Development funded Marine Business & Technology Centre, which is supporting Devon-based SMEs through research, testing, proving and production.
- Smart Sound Plymouth - Britain's premier proving area for designing, testing and developing cutting edge products and services for the marine sector.
- Future Autonomous at Sea Technologies - a group of industry leading companies and organisations working towards the delivery of autonomous at sea solutions, which is headed up by PML's Dr James Fishwick.
- Public bodies - for example, PML's Head of Science for Sea & Society, Prof. Mel Austen, was seconded to work for one day per week as the first Chief Scientific Advisor for the Marine Management Organisation for a period of 3 years (September 2010 to September 2013).

Recognition & Reward for Carrying Out Research and Achieving Impact: All scientific staff are primarily engaged to undertake or support research leading to impact. Where there is a particular activity that is deemed worthy of an additional reward, then the bonus scheme may be applied.

There is a *Rewards to Inventors* scheme in place in recognition of those scientists whose inventions may lead to income derived from licensing of intellectual property, spin-out companies, etc.

Scientists are provided with support to achieve impact from their research in a number of ways:

- Regular workshops held to understand impact, theory of change and the development and use of logframes.
- Significant guidance materials have been developed for staff, including the planning for and evaluation of impact, and impact case studies. Scientists are supported by staff with particular expertise in impact to help draft Pathways to Impact.
- A dedicated impact team is in place to support scientists where needed.

Training & Supervision (Post Graduate and Under Graduate Research students)

PML created the role of a Head of Postgraduate Studies in June 2014 to provide a focal point for the co-ordination of student activity, training and pastoral care within the laboratory.

PhD Students: In the period under review PML has hosted 53 PhD students, and has also co-supervised many others.

PML is currently part of two NERC-funded Doctoral Training Partnerships (DTP):

- GW4+ which includes the Universities of Bristol, Bath, Exeter, Cardiff, and current and former NERC Centres, and the Natural History Museum.
- ARIES which includes the Universities of East Anglia, Essex, Kent, Plymouth, and Royal Holloway College, University of London, as well as other collaborators.

PML was a member of the NERC-funded University of Southampton SPITFIRE DTP (2013–2018).

In all cases PML participates as a full member of the DTP management board. PML supervisors are required to undergo university approved supervisor training before taking on their first student.

Masters Students: PML staff supervise visiting Masters' students (both MRes and MSc) as they undertake their final projects. The students are from a wide number of UK universities although the majority are registered at the Universities of Plymouth and Exeter.

Undergraduate Students: PML supervises UK undergraduate student Honours projects and voluntary work-placements. PML regularly hosts visiting Erasmus programme students from a variety of international universities. PML also provides a "Marine Ecology" module to 50 students from the University of Exeter Marine Science degree course.

Equality and Diversity (E&D)

In May 2018 PML successfully achieved **bronze level Athena SWAN accreditation** in recognition of its gender equality and representation and inclusive culture in the workplace. Significant contributions were made by staff at all levels and across gender to achieve this accolade.

PML has an E&D policy in place which has recently been reviewed and extended to cover Inclusion. Staff have received some training in E&D. A comprehensive report on E&D and Inclusion (E&D&I) has been produced, which identifies trends to date, E&D&I actions to be implemented and data to be captured particularly on protected characteristics.

The activity continues with regular workshops, which are promoted across the organisation, on specific topics, e.g. neurodiversity, and staff surveys, as part of continuous monitoring and progression.

An active Athena SWAN Committee (composition 6 males; 8 females) is working towards submission for silver level Athena SWAN accreditation in 2021.

Income, Infrastructure & Facilities

Income

PML's Science Plan was delivered through a wide variety of funding streams from a diverse portfolio of public, private and third sector customers and stakeholders. PML has maintained and expanded its customer base, which in the period 2013-2019 included 68 different funding bodies from the UK, Europe and elsewhere, including foundation funding, with our largest customers being NERC (including National Capability), Global Challenges Research Fund (GCRF), the European Commission and the European Space Agency.

Some of this expansion uses PML Applications Ltd. Currently PML Applications focuses on science applications for ballast water management, biofouling and corrosion, satellite (geospatial) applications and environmental solutions. Growing this funding base is a priority in the implementation of PML's strategy allowing the charity to invest sustainably in itself.

Income at Group level over the previous six financial years averaged £11.6M pa. Further details on finances can be found in Section B: Data. PML's income has grown year over the period from £10.65M in FY2013/14 to £11.79M in FY 2018/19. PML made a surplus every year part from 2016. PML's results are audited at Group level (includes PML Applications' income).

The current financial year's turnover for PML is forecast at £12M and for PML Applications at £1.6M. PML has assets valued at £12M including free reserves of £2.3M.[11]

PML currently derives c.32%[12] of its income as a NC provider with the remainder derived from CR sources, which comprise a mix of funders including NERC, other Research Councils, UKRI Global Challenges Research Fund (GCRF), other government departments, the European Union, the European Space Agency (ESA), and charitable foundations.

As an NC delivery partner PML delivers Marine NC (*via* NOC) and Earth Observation NC (*via* the National Centre for Earth Observation [NCEO[13]]). In addition PML is in receipt of institutional funding.

Our single centre marine NC is a component of the NOC led Climate linked Atlantic Sector Science CLASS programme, comprising 3 underpinning activities the AMT, the WCO and the ERSEM, and contributions to research themes on Carbon and Ecosystems.

The Long Term Science Multiple Centre programmes, all delivered with various NERC Centres, started in April 2016. PML's activities are as follows:

- Ocean Regulation of Climate through Heat and Carbon Sequestration and Transports (ORCHESTRA)
- Land Ocean Carbon Transfer (LOCATE)
- The North Atlantic Climate System Integrated Study (ACSIS)
- UK Earth System Modelling (UKESM) Project

Overseas Development Assistance (ODA) NC started in April 2017.

[11] PML audited accounts 2018-19
[12] Based on forecast for FY 2019-20
[13] https://www.nceo.ac.uk/

ACCORD: PML is working in close cooperation with NOC and regional or national government partners in Vietnam, Malaysia and Cambodia thus facilitating the direct application of project results into environmental policy and governance.

PML is a partner in NCEO with PML's science role to improve estimates of ocean carbon fluxes from bio-geochemistry data assimilation, using EO data such as ocean Sea Surface Temperature and ocean colour.

PML has been successful in leading major programmes funded in partnership by NERC and various government departments, e.g. the UK Ocean Acidification Research Programme (2010–2016) – funded jointly with DECC and DEFRA, and the Marine Ecosystems Research Programme (2014–2018) funded jointly with Defra.

PML runs an internal assessment process for NERC research grant applications and has never been placed under demand management measures by NERC for discovery science. Since 2013 PML has been awarded 8 grants of £1.67M total value from this funding scheme.

PML has developed a strategy to obtain funding from charitable sources, and in the last 5 years has had success with a number of different foundations. In 2018 the PML Board invested in a dedicated fundraiser to help drive this growth.

Infrastructure & Facilities

Specialist Research Infrastructure and Facilities: PML (and PML Applications) is located primarily on one main site, which enables excellent collaboration amongst staff, with a small unit located within Oceansgate (a marine enterprise hub in Plymouth) for engaging with local marine industries.

Resources and infrastructure, such as ships, buoys and a mesocosm facility, provide our scientists with the tools to conduct meaningful research. A sizeable (200 seats) modern lecture facility enables our scientists to host large conferences and to share their knowledge and findings with fellow scientists, key stakeholders and the wider public. In order to deliver world-class science PML maintains state-of-the-art infrastructure and facilities.

A £5.5M refurbishment programme completed in February 2019, funded by NERC (£5M) and £500k of PML's reserves comprising:

- Bespoke clean microplastics research facility
- Refurbished, biodiversity, ocean biogeochemistry and air-sea gas laboratories
- New offices and teaching laboratories for our postgraduate students
- New laboratories and office facilities for PML Applications
- New reception, staff recreation area and additional meeting rooms
- Smart Sound, mesocosm and molecular matrix (see below)

PML Mesocosm: A controlled aquatic environment which allows scientists the ability to manipulate a range of environmental factors, such as salinity, pH, temperature and oxygen levels on plankton and invertebrates.

The Smart Sound Laboratory: Designed for testing and development of pioneering scientific sensors and platforms. It also includes optical biogeochemistry laboratories for testing and calibration of bio-optical instrumentation supplemented by co-located mechanical and electronic workshops providing support to these highly technical science areas.

Molecular Matrix: A state-of-the-art suite of laboratories dedicated to the study and culture of marine organisms (viruses, bacteria, archaea, fungi and plankton), molecular ecology and biotechnology. In 2016 a £1M single-cell genomics facility was opened which allows the direct

isolation and characterisation of unicellular organisms and viruses from natural samples providing unprecedented genomic resolution to the field of oceanic microbial ecology. The High-Speed Atomic Force Microscope provides nanometre resolution for imaging millimetre sized areas or real-time videos of dynamic nano- or micro-scale structures or surface processes of environmental organisms.

Research Vessels: The *Plymouth Quest* is a 21.5m coastal research vessel capable of undertaking sampling, fishing, buoy deployment and recovery, undergraduate field courses and contract work for a number of commercial partners in the coastal seas off Plymouth. The *PML Explorer* is a rigid hulled inflatable boat which supports inshore and estuarine research.

Atmospheric Observatory: The Penlee Point Atmospheric Observatory (PPAO) was established by PML in 2014 for long-term observations of ocean-atmosphere interaction and forms part of the WCO.

Data Buoys: PML has been operating two data buoys in the western English Channel (at stations L4 and E1) since 1999, each equipped with an array of sensors to measure both atmospheric and marine parameters. In 2013 a new buoy was deployed at station E1 in collaboration with the UKMO, sharing expertise to deliver a state-of-the-art multi-user platform. With funding from the European Regional Development Fund received in 2018, PML will add to its capabilities through a new in-water profiling data buoy (£300k).

Bio-Argo: PML deploys and maintains the 13 UK float bio-argo fleet (£0.5M) funded by NERC, contributing to a larger international effort of over 300 floats.

High Performance Computing: PML has extensive computing facilities, within a dedicated modern computer room. We have invested ~£2.6M over the period, funded through, NERC capital, CR and PML reserves as follows:

- High throughput computing (HTC) system interconnected with fast networking and approximately 5 PB of networked storage for processing Earth observation data.
- High performance computing (HPC) cluster providing a facility for model testing and smaller scale simulations that don't require national HPC facilities.
- A GPU cluster currently being installed (£1M NEODAAS capital), to explore machine learning approached environmental data analysis.

Lecture Theatre: a 200 seat, modern facility enabling PML scientists' to share knowledge with many stakeholders. It is regularly used for seminars, training events, national and international conferences and stakeholder workshops.

NERC Service and Facilities

PML runs the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) for NERC through NCEO. NEODAAS offers services including: systematic acquisition and processing of data from a number of satellites, near-real time support and rapid response using satellite data, airborne data processing, development of new products and user support. During the assessment period NEODAAS supported 33 research cruises and provided custom data processing for 89 projects, contributing to 354 journal articles. The NERC Airborne Research Facility-Data Analysis Node, now part of NEODAAS, processed 163 flights of airborne data.

WCO Sample Collection: PML holds preserved samples for eDNA, marine microbes, plankton and benthos from the WCO long-term biological time series.

Oceansgate: (£150k) in 2018 office facilities for business development and a new storage facility were created at the Oceansgate[14] marine enterprise zone. A presence in Oceansgate will give PML greater visibility in the local business community.

New Business System: (£530k) for finance and contracts management was implemented in 2019.

Operational and Scholarly Infrastructure Supporting Research and Impact

Board of Trustees: of whom there are currently eight (5 male; 3 female), have control of PML's property and funds; they make decisions on reinvestment of reserves into PML, including funds to be released for investment in facilities, infrastructure and strategic scientific appointments. The Trustees possess a wide range of skills, including strategic leadership, science, commercial application of science, financial, business and HR.

Reporting by PML is undertaken annually to the Charities Commission and Companies House through its Trustees' Report and Accounts, completed in accordance with Charity Commission requirements, and which are externally audited.

Operational Infrastructure: The operations groups (Figure 1) are responsible for advising SMT on operational strategic objectives and ensuring service delivery to internal and external stakeholders. They report to the Chief Executive (the organisational structure is currently under review). The groups are as follows;

- Corporate Affairs (Communications, Marketing, Fundraising and administrative support for science)
- Financial services (including Contracts)
- Human Resources
- Information Technology
- Quality Management (ISO accreditation)
- Technical Services (estates and building management)

Other bodies have been established to handle specific remits within PML: Health & Safety Committee, Scientific Data Management Committee, Education & Training Committee, Environmental Management Committee, etc, Each has its own Terms of Reference and reports directly to either the ST or SMT as appropriate. Health & Safety is a standing agenda item for the PML and PML Applications' Boards, SMT and ST of PML, and the Executive of PML Applications Ltd.

Library Service: National Marine Biological Library (NMBL), based at the Marine Biological Association (MBA) in Plymouth UK, is one of the largest marine reference libraries in the world and supplies PML with electronic journal access to major marine and environmental journals.

Use of Major Research Facilities both in the UK and Overseas

NOC & BAS Ship Services: PML makes extensive use of the NERC research fleet to deliver large projects and programmes, e.g. Shelf Seas Biogeochemistry, Changing Arctic Oceans, and ORCHESTRA. The annual AMT cruise exploits the southward passage of the *James Clark Ross* to the Antarctic in the austral spring.

National HPC: The PML modelling group uses ARCHER, the UK National Supercomputing Service to deliver, for example, large regional climate forced simulations required for NERC strategic

[14] http://www.oceansgateplymouth.com/

programmes and NC. MONSooN delivers supercomputing infrastructure to enable collaboration between NERC and UKMO scientists: for example, the Joint Weather Climate Research Programme UK Environmental Prediction Programme is a partnership with NERC Centres to build and evaluate a high resolution regional coupled prediction system for the UK.

NERC Data Services: PML is a supplier and user of oceanographic and Earth observation data with the British Oceanographic Data Centre (BODC) and the NERC Earth Observation Data Centre at the Centre for Environmental Data Analysis.

Use of International Infrastructure: PML has previously accessed these to deliver against collaborative international projects, e.g. Mesocosms in NIVA (Norway) and German research ships (*Poseidon*).

Collaboration and Contribution to the Research Base, Economy and Society

Effectiveness of Research Collaborations, Networks and Partnerships

PML demonstrates strong research collaborations and provides national and international leadership across all of its science activities. PML has published with scientists from over 1800 different organisations in 85 different countries. The top 5 countries are USA (24.9%), France (17.3%), Germany (15.8%), Italy (12%), and Australia (11.55%), and the top five organisations are the University of Exeter (11.5%), the University of Plymouth (10.4%), the University of Southampton (8.8%), NOC (8.4%), and the National Oceanic and Atmospheric Administration, US (4.3%).

Staff are encouraged and mentored in developing such networks through participation in relevant conferences, meetings and, more recently, through virtual participation to support staff less able to travel.

National and International Leadership

- PML (PI Somerfield) led the NERC/Defra funded Marine Ecosystems Research Programme (MERP)[15].
- PML (PI Blackford) led the first study that quantified the detectability and environmental impact of leakage from a controlled sub-seabed release of CO_2 thereby identifying appropriate monitoring strategies for full-scale carbon capture and storage operations. (NERC QICS[16] project, Blackford *et al*., 2014).
- ESA Climate Change Initiative: PML led (PI Sathyendranath) a European consortium to deliver climate quality ocean colour data products[17].
- The H2020 MONOCLE[18] project (PI Simis) is developing Multiscale Observation Networks for Optical monitoring of Coastal waters, Lakes and Estuaries.
- PML (Findlay) sits on the international executive group for the GOA-ON and coordinates the GOA-ON North East Atlantic regional hub.

[15] https://www.marine-ecosystems.org.uk/Home
[16] https://www.bgs.ac.uk/qics/
[17] https://esa-oceancolour-cci.org/
[18] https://monocle-h2020.eu/Home

Relationships with Key Research Users, Beneficiaries or Audiences

Examples of interactions and engagement with key researchers, beneficiaries and audiences to develop impact from PML's activities are as follows:

- MERP led by PML: regular stakeholder engagement, particularly with policy makers and environmental managers. An interactive tool[19] was produced from MERP to address key policy questions, such as, "Are we achieving Good Environmental Status?" (a requirement under the Marine Strategy Framework Directive).
- Delivering DEFRA's aspirations at UNFCCC COP25.
- PML is a member of Maritime UK South West and chairs the Future Autonomous at Sea Technologies cluster.
- PML is part of the South West Partnership for Environmental and Economic Prosperity (SWEEP) project. PML has provided model projections and a report relating to climate change to the Marine Management Organisation (MMO) to inform the South West Marine Plan area.
- ACCORD: developed strong links with national (Cambodia) and provincial (Vietnam) government departments and these links have facilitated links to in country universities, e.g. Da Nang and Hue, and NGOs, e.g. Marine Conservation Cambodia.
- High level visits to PML included: ministerial visits, MPs, Chief Scientific Advisor and Head of Evidence of the MMO, Chief Scientific Advisor to the Foreign & Commonwealth Office, WWF, Worldfish, Global Business Partnerships of Nova Scotia Business delegation from the National Institute of Ocean Technology, India.

Wider Contributions to the Economy and Society

Examples include:

- 211 mentions of PML research papers produced during the assessment period in policy documents, including UK Government and UN policy documents, and Parliament Briefing notes.
- Before 1987, the use of Tributyltin (TBT) and similar anti-fouling chemicals caused severe harm to shellfish and other marine life. Decades of research at PML and the MBA, made a fundamental contribution to the UK successfully banning these harmful pollutants resulting in a £908M net benefit to the UK up to 2014 (Deloitte report[20] and NERC Impact Report 2016[21]).
- PML has been exploring the potential of hydrothermal liquefaction (HTL) of algal biomass, a thermal depolymerization process to convert wet biomass into bio-oil and at the same time remove environmental waste. It was found to be effective in partitioning contaminant metals (Raikova *et al*., 2016).
- PML Applications has developed a next generation in-water hull cleaning system, which provides an environmentally sound solution, and which reduces ships' fuel costs and emissions, and the risk of transportation of invasive species.
- PML has optimised the use of satellites to detect oil spills, and in April 2019 identified an oil spill in the Malacca strait, alerted authorities, so avoiding an environmental disaster and saving an estimated £1.5M in clean-up costs.
- PML is currently engaging with the Connect Academy Trust, a trust of five primary schools with 2200 pupils to develop an ocean curriculum.

[19] https://www.marine-ecosystems.org.uk/Research_outcomes/Policy_Interactive
[20] https://nerc.ukri.org/about/perform/evaluation/evaluationreports/tributyltin-and-biocides/
[21] https://nerc.ukri.org/about/perform/reporting/reports/impactreport2016/

Engagement with Diverse Stakeholders and the Public through its Research

Examples include:

- PML research papers are promoted *via* PML's social media, through its dedicated PML papers Twitter feed, and general Twitter feed, and by paper authors' own social media channels.
- The successful of the promotion of PML research during the assessment period *via* social media generated 23,514 mentions in social media across 148 countries and 867 times in news outlets worldwide[22].
- Working with stakeholders in Mauritius the Coral Communities project successfully piloted a novel, arts-based approach for assessing perceptions of the environment and the socio-cultural risk associated with different resilience strategies.
- PML and the University of Plymouth held a public poetry and science event "Crosscurrents" in 2017 featuring talks and readings from five pairs of poets and scientists to explore subjects ranging from algal blooms to ecosystem modelling.
- Scientists have given presentations to the University of the Third Age, the Children's University, and engaged in Soapbox Science (Bringing Science to the People) and British Science week.
- PML scientists and communications team contributed as lead authors to the Youth Guide to the Ocean (a Food & Agriculture Organization of the UN publication 2015).
- *Painting by Numbers* – TEDx talk on the colourful world of marine satellite imagery.
- Marine Tech Expo, showcasing the latest marine innovations in ocean technology to industry.

Contribution to the Sustainability of the Discipline

Evidence includes:

- PML is a member of the Partnership for Observation of the Global Ocean (POGO)[23] (and hosts its secretariat) which serves as a forum for leaders of major oceanographic institutions around the world to promote global oceanography, particularly the implementation of international and integrated global ocean observing systems.
- PML is a member of the Partnerships in Environmental Management for the Seas of East Asia (PEMSEA) an intergovernmental organization operating in East Asia to foster and sustain healthy and resilient oceans, coasts, communities and economies across the region. This is particularly relevant for the ODA work in which PML is involved.
- PML leads the Advances in Marine Ecosystem Modelling Research conference series to present, discuss and learn about marine modelling challenges, methods, applications and outcomes.

Interdisciplinary Research with Impact: PML takes an interdisciplinary, science-based approach, which allows it to address large, complex environmental topics or issues in a holistic way; identifying key interactions, feedbacks and trade-offs between the process involved. The AMT and Blue Communities are exemplars of our approach**.**

Atlantic Meridional Transect (AMT) is an exemplar of national and international scientific collaboration, a training arena for the next generation of oceanographers and an ideal facility for validation of novel technology. Since 1995 the 29 AMT cruises have hosted over 220 scientists

[22] Source Altmetric
[23] http://ocean-partners.org/

(from over 60 research institutes in 18 countries), produced over 300 ISI papers and contributed to over 75 PhD studies. Examples of significant outcomes include:

- Clear evidence of ocean acidification across 100° of latitude in the Atlantic Ocean (Kitidis *et al*., 2017).
- Showed that surfactants exert a control on air-sea CO_2 exchange across the whole North Atlantic CO_2 sink region (Sabbaghzadeh *et al*., 2017).
- Determined that both respiration and photosynthesis determine the scaling of plankton metabolism in the oligotrophic ocean (Serret *et al*., 2015).
- 8 international fellows participated in cruises funded by POGO.
- 7 cruises have taken place and 107 papers published based on AMT data.

GCRF Blue Communities[24] is a £6.7M international consortium (PI Austen) which is working to support the development, implementation and ongoing management of initiatives that promote the sustainable use of marine resources by multiple users, whilst protecting the fragile marine ecosystems and supporting the livelihoods, food security, health and well-being of the people in these coastal communities.

Responsiveness to National and International Priorities and Initiatives

- Participation in: the United Nations (UN) General Assembly in relation to ocean acidification (June 2013); the 15th UN Open-Ended Informal Consultative Process on Oceans and the Law of Sea – Oceans & Food Security (May 2014), and the UN Ocean Conference to support the implementation of SDG14 (June 2017).
- Delivering DEFRA's requirements at UNFCCC COP25.
- Involvement in the UK planning activities for the UN Decade of Ocean Science for Sustainability, and input provided to the Intergovernmental Oceanographic Commission on the Decade's priorities (partner contribution) (2019 and ongoing).
- Dr Tom Bell is a UK representative for the international Surface Ocean-Lower Atmosphere Study (SOLAS) programme.
- PML's Prof. Mel Austen was appointed by the minister to the UK Government's Natural Capital Committee and has been engaged in the implementation of the 25 Year Environment Plan.
- Parliamentary and other inquiries: PML has provided evidence to 29 inquiries (2013-2019) on subjects such as public understanding of climate change, food security, carbon capture and storage, the Arctic, MPZs and valuing marine ecosystems, nitrate pollution and microplastics in the marine environment.

Indicators of Wider Influence, Contributions to and Recognition by the Research Base

PML scientists are editors of journals, examples of which are: Marine Chemistry, Journal of Atmospheric Physics & Chemistry, Journal of Ecology, Polar Biology, and Marine Biology, as well as guest editors of Deep Research. PML scientists also engage in the review of publications, e.g. Nature journals, Science of the Total Environment, Marine Ecology Progress Series, Marine Environmental Research.

PML scientists have also been, or currently are review editors or lead authors on the IPCC Assessment Reports on Climate Change.

[24] https://blue-communities.org/Home

PML scientists have been or are currently members of the NERC Peer Review College. There are currently five serving members from PML.

PML scientists are members of numerous (>110) national and international committees, examples of which are:

- the Board of the Canadian Healthy Oceans Network
- OSPAR Intersessional Correspondence Group on Ocean Acidification
- Sustainable Development Goal (SDG) Informal Preparatory Working Group 3
- Advisory Board for the Ocean Acidification International Co-ordination Centre (Chair)
- International Council for Exploration of the Sea working groups
- International Advisory Board of the Centre for Ocean Life
- Global Ocean Acidification Observing Network
- Chlorophyll Global Integrated Network
- Arctic in Rapid Transition Network
- Joint Nature Conservation Committee
- National Partnership for Ocean Prediction
- Productive Seas Evidence Group

PML has attracted external scientists with fellowships and also obtained fellowship funding for its own scientists. During the assessment period PML has hosted 3 Marie Curie fellowships, and 1 Newton International Fellow and has obtained funding from fellowship schemes operated by the European Space Agency, NERC (KE Fellowship), the Japan Agency for Marine-Earth Science and Technology, and the Jawaharlal Nehru Centre for Advance Scientific Research.

Organisationally and individually, the following awards or measures of esteem have been won during the assessment period:

- Dr Shubha Sathyendranath was awarded the N.K. Panikaar medal by the Intergovernmental Oceanographic Commission/UNESCO for her contributions to capacity building, especially for young scientists and in the developing world (2013).
- Dr Shubha Sathyendranath was awarded the Grande Médaille Prince Albert 1er for 2013 bestowed by the Institut Océanographique, Monaco (2014).
- PML won the national Charity Awards Environment & Conservation category (2014).
- PML Earth observation scientists won first prize from the European Space Agency for their web-based lesson on phytoplankton seasonality using satellite ocean-colour in the Red Sea (2014).
- PML was ranked 6th in the world, and the top institute in the UK, by the International Center for Climate Governance (2015).
- PML student, Alice Wilson McNeal, was the overall winner of the P1 Marine Foundation National Student Awards for her project “Plankton eating plastic: worth worrying about?” (2015).
- PML was part of a team of researchers with colleagues from the Universities of Exeter and Plymouth who won the NERC Impact award (societal impact category), and the Overall Impact Award (2018).
- Prof Pennie Lindeque received the Highly Cited Researcher award from Web of Science in the field of Environment and Ecology (2019).

Examples of keynote speeches/invited lectures by PML scientists include:

- The Australian Agricultural & Resource Economics Society Conference – invited lecture on ecosystem services approach (2013).
- North Pacific Marine Science (PICES) Open Science Meeting – keynote speaker on ecosystem response to climate (2014).
- Marine Environmental Observation, Prediction and Response Expert Forum, Canada – keynote speaker – the Arctic and ocean acidification (2015).
- World Ocean Council Sustainable Ocean Summit – invited speaker (2016).
- European Parliament Recreational Fisheries Forum – invited speaker on Marine Protected Areas and recreational fisheries: sustainable management (2017).
- Lessons from two high CO_2 Worlds, Azores – keynote speaker on ocean acidification science to policy (2018).
- Royal Society – debate on marine plastics – invited speaker on ocean plastics (2019).

Data on conference chair roles has not been captured in the assessment period, but these are activities which PML scientists fulfil.

Training

PML provided training in the application of operational Earth observation data from COPERNICUS to Marine Meteorology and Ocean Applications funded by EUMETSAT. Courses were held in South Africa, Morocco, the Philippines and Ghana aimed at building capacity with PG and EC researchers.

ENVIRONMENT COMPONENT DATA

Total income (funding and capital): £m

2013/14	2014/15	2015/16	2016/17	2017/18	2018/19
10.65	12.11	12.06	10.64	10.57	16.79

Open access data

	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	Notes
UKRI open access block grant awarded to the Centre (£k)	14.1	16.6	18.9	0	23.0	37.0	Rolled over in years when not fully used.
% of UKRI open access block grant spent (for years where block grant was received)	35%	149%	47%		52%	129%	
PML spend on open access (£k)	5.0	24.7	8.9	0	11.8	47.8	
% **overall** open access compliance for UKRI-funded papers (as reported to UKRI)	45%	50%	65%	90%	95%	98%	*We have endeavoured to make all publications available as OA on our repository from 2016 onwards (following RCUK OA policy). We estimate the number available as OA based on dip-testing as our repository is unable to capture this information*
% **gold** open access compliance for UKRI-funded papers (as reported to UKRI)							*Our repository system does not capture this information. It is not possible to estimate as we cannot report by funders from our repository system. We will review to capture in future.*
% **green** open access compliance for UKRI-funded papers (as reported to UKRI)							