Section A

Institution: University of St Andrews

Unit of Assessment: UoA 10: Mathematical Sciences

Title of case study: Statistical research reduces environmental impact in the world's oceans

Period when the underpinning research was undertaken: 01 August 2011 - 31 January 2017

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by HEI:**
Len Thomas	Professor	01 April1997 - present
Monique Mackenzie	Senior Lecturer	01 February 2003 - present
Lindesay Scott-Hayward	Senior Research Fellow	18 July 2011 - present

Period when the claimed impact occurred: 01 August 2013 - 30 September 2020

Is this case study continued from a case study submitted in 2014? No

Section B

1. Summary of the impact

Statistical methods developed by Prof L. Thomas and colleagues have been used across a range of marine industries to assess and reduce the environmental impact of human activities on marine mammals and seabirds.

- The US and 4 European navies use our statistical methods for quantifying behavioural disturbance to help manage their use of sonar in ways that meet environmental regulations and reduce adverse impact.
- Natural England, Marine Scotland, and UK industry bodies recommend our method for estimating the displacement of animals in response to installation of offshore wind turbines; they have been used in the consenting process or post-consent monitoring in at least 13 wind farms in the UK and Denmark that will power over 4,500,000 homes.
- Our research was a key component of the Deepwater Horizon oil spill natural resources damage assessment, which BP settled for USD20,800,000. It has changed the way the US government approaches damage assessments.

2. Underpinning research

Underwater noise can cause disturbance to marine mammals and seabirds, resulting in changes in behaviour that may have chronic long-term consequences on the population. Loud underwater noise is produced by several industries, including the world's navies (where powerful sonar is used to hunt submarines) and the marine renewables industry during wind-farm construction (where pile driving is often used to install the towers). Historically, little has been known about these effects. Nevertheless, many nations have regulations that require statements of environmental impact in order that activities can be approved.

To understand the response of marine mammals to naval sonar, several NATO navies (US, UK, Norway, Netherlands, France) have funded multi-million-pound (equivalent) research programmes to develop and undertake behavioural response studies (BRSs). In these studies, wild-swimming animals are located, motion-sensitive tags are temporarily attached to them, a sonar (or control) playback is performed, and the tag is retrieved. Such experiments are characterised by low sample sizes of individuals but large quantities of multivariate data, which is collected from different sources (tags, visual observers, acoustics) at different scales. Suitable analysis methods were lacking for determining whether marine mammals respond to sonar and under what circumstance; this led to a US Navy-funded research project (MOCHA, between 2012 and 2015) led by Thomas. Methods were developed for determining whether a behavioural response had occurred using a multivariate data reduction technique (Mahalanobis distance), and for estimating the probability of response as a function of sonar dose metrics such as received acoustic level ("dose-response function") using a hierarchical Bayesian approach [R1]. Concurrently, Thomas supervised the part-time PhD of a US Navy employee who developed methods for estimating dose-response functions from observational data collected by arrays of underwater microphones on US Navy testing ranges [R2].

In research led by Mackenzie and Scott-Hayward (between 2013 and 2016), we have also developed novel spatially adaptive modelling methods to quantify the environmental impact of wind farm construction in terms of spatial displacement of animals [R3]. This work has one and two-dimensional (spatial) smoother-based modelling methods at its heart. Spatial modelling methods (CReSS) [R3], combined with a model selection algorithm, enable realistic quantification of wildlife distribution and displacement even in areas with complex topography such as around coastlines. This work was extended to be appropriate for data collected over time [R4], such as data collected along transects from aircraft undertaking high resolution digital surveys. The outputs from these methods have a key role in the environmental statements for the consenting process of new wind farms and the ongoing monitoring post construction. Removing barriers to consenting renewable energy schemes is an important part of the strategy to reduce carbon emissions.

A major cause of environmental impact in some locations is chemical pollution. The Deepwater Horizon explosion in 2010 resulted in the largest ever oil spill in US waters – approximately 3,200,000 barrels. A natural resources damage assessment was required by law, and an important component of this was an assessment of both short- and long-term consequences for marine mammal populations. Information available to make this assessment was complex, diverse and patchy.

The marine mammal component of the Deepwater Horizon damage assessment was undertaken by a team assembled by the US National Oceanographic and Atmospheric Administration (NOAA). This included Thomas, who led or co-led on research partitioning mortality into stocks by combining multiple incomplete datasets using a hierarchical Bayesian model [R5], estimating mortality from mark-recapture data using a novel Bayesian spatial capture-recapture approach, and creating a population dynamics model to predict the population recovery trajectory [R6].

3. References to the research

St Andrews School of Mathematics and Statistics staff in **bold**. All outputs published in international, peer-reviewed journals.

[R1] Miller, P.J.O., R.N. Antunes, P.J. Wensveen, F.I.P. Samarra, A. Catarina Alves, P.H. Kvadsheim, L. Kleivana, F.-P.A. Lam, M.A. Ainsle, P.L. Tyack and **L. Thomas**. 2014. Dose-response relationships for the onset of avoidance of sonar by free-ranging killer whales. Journal of the Acoustical Society of America 135: 975-993. DOI: 10.1121/1.4861346

[R2] Moretti, D., **L. Thomas**, **T. Marques**, J. Harwood, A. Dilley, B. Neales, J. Shaffer, E. McCarthy, L. New, S. Jarvis and R. Morrissey. 2014. A risk function for behavioral disruption of Blainville's beaked whales (*Mesoplodon densirostris*) from mid-frequency active sonar. PLoS ONE 9(1): e85064. DOI: 10.1371/journal.pone.0085064

[R3] **Scott Hayward, L. A. S.**, **MacKenzie, M. L.**, **Donovan, C. R.**, Walker, C. & Ashe, E. 2014. Complex Region Spatial Smoother (CReSS). Journal of Computational and Graphical Statistics. 23: 340-360. DOI: 10.1080/10618600.2012.762920

[R4] **Scott Hayward, L. A. S.**, **MacKenzie, M. L.**, Ashe, E. & Williams, R. 2015. Modelling Killer Whale Feeding Behaviour Using a Spatially Adaptive Complex Region Spatial Smoother (CReSS) and Generalised Estimating Equations (GEEs). Journal of Agricultural, Biological and Environmental Statistics. 20: 305-322. DOI: 10.1007/s13253-015-0209-2

[R5] **Thomas, L.**, C.G. Booth, P.E. Rosel, A. Hohn, J. Litz and L.H. Schwacke. Where were they from? Modelling the source stock of dolphins stranded after the Deepwater Horizon oil spill using genetic and stable isotope data. 2017. Endangered Species Research 33: 253-264. DOI: 10.3354/esr00754

[R6] Schwacke, L.H., **L. Thomas**, R.S. Wells, W.E. McFee, A.A. Hahn, K.D. Mullin, E.S. Zolman, B.M. Quigley, T.K. Rowles and J.H. Schwacke. 2017. Quantifying injury to common bottlenose dolphins from the *Deepwater Horizon* oil spill using an age-, sex- and class-structured population model Endangered Species Research 33: 265-279. DOI: 10.3354/esr00777

4. Details of the impact

The research in statistics at the University of St Andrews, as listed in Section 2, has underpinned environmental impact assessments for marine mammals and seabirds across a range of marine industries worldwide. There are 3 main areas of impact in this REF period:

- **In defence**, as a result of our methods, **the US and 4 other NATO navies have changed procedures to demonstrably manage their use of sonar** to meet environmental regulations and reduce adverse effects on marine animals.
- **In marine renewable energy**, our methods are recommended by national agencies (UK and Scotland), and these have been adopted by industry bodies when **assessing the environmental impact of wind farm construction**. When significant impacts have been evidenced, this has required an industry response such as additional monitoring alongside an independent evaluation of the ability of the monitoring to detect population recovery post-construction.
- **In oil production**, our research contributed to the **Deepwater Horizon oil spill natural resources damage assessment**, which led to the largest environmental damage settlement in US history. The analytical approaches developed have **changed the way the US government approaches damage assessments**.

Changes to the way navies effectively manage sonar usage

Navies of the world have identified active sonar as a key component of anti-submarine warfare. To ensure they are ready to use it effectively, Navies conduct frequent training and testing activities. The loud underwater sounds produced during these activities have the potential to harm marine life. Most nations, therefore, require procedures to be followed that minimise any harm, and also some form of environmental assessment. Our research has helped the navies of the US, UK, Netherlands, France and Norway to (a) demonstrate compliance with their country's environmental regulations and/or (b) to change their operating procedures to reduce the impact of sonar on marine mammals.

The US Navy is required to submit environmental impact statements (EISs) or overseas EISs (OEISs) to the National Oceanographic and Atmospheric Agency (NOAA) for each training and testing area (typically many millions of square km) between every 5 and 7 years. These include requests to "take" a specified number of marine mammals (at specified taxonomic levels, e.g., species), where the definition of a take includes certain types of behavioural disturbance. To estimate the number of takes, the Navy has built a simulation tool, Navy Acoustic Effects Model (NAEMO). One key input is the dose-response function – i.e., the probability of a response as a function of acoustic dose. The most recent set of EIS/OEISs (Phase III EIS) were written between 2014 and 2018. For these, at the request of the Navy environmental compliance team, Thomas and a PhD student developed custom biphasic dose-response functions, based on our previous Bayesian dose-response modelling methods [R1]. These were used in deriving the dose-response functions used in the EIS/OEISs [S1, S2]. Additional input data for these analyses used (a) methods we developed for determining whether a behavioural response has taken place during Behavioural Response Studies (BRSs) [R1], and (b) results from observational studies of acoustic response on Navy testing ranges [R2] undertaken by a Navy employee as part of their part-time PhD supervised and assisted by Thomas at St Andrews [S1,

p. 65; S2]. In summary, as stated by the Director of the Energy and Environmental Readiness Division, Department of the Navy "…*statistical developments by researchers in Math and Statistics at St Andrews, have provided critical scientific bases for the EIS/OEIS that enable the Navy to obtain permits authorizing continued training and testing on at-sea ranges*." [S2]

Many European navies have used BRS data analysed with our methods to develop tools for planning sonar exercises and as real-time decision aids used on the bridge of warships. Examples include the UK S2117, Netherlands SAKAMATA and Norwegian SONATE. For example, the Norwegian Navy's guidance for planning of intense sonar exercises is based on results from the study where we first developed the Bayesian dose-response methods [R1, S3]. In addition, the UK, Netherlands, French and Norwegian Navies have changed specific operating procedures to reduce the impact of sonar on cetaceans, based on published research where we played a key role in the analysis [R1 and others, S3, S4]. The Chief of Staff, Royal Norwegian Navy, writes "… *the ground-breaking research of the University of St Andrews and their international partners has resulted in major advances in our ability to manage the use of sonar. The impact of this research is that we are able to use sonar with restrictions and guidance based upon scientific evidence of effects on cetaceans. The research has been critical for developing and underpinning our guidelines, which protect the marine environment by reducing sonar impacts on cetaceans while allowing the Norwegian Navy to train and conduct our sonar activities without unnecessary restrictions*." [S3] The Director of Department Maritime Systems, Royal Dutch Navy writes "*NATO established the Active Sonar Risk Mitigation Smart Defence Initiative in 2014 to harmonize procedures designed to mitigate the risk of active sonar operations by NATO navies. … The biological and statistical research conducted by the University of St Andrews has profoundly influenced our understanding both of which types of effects are considered, and how to quantify and reduce risk during planned sonar exercises*." [S4, pp. 2-3]

Enabling assessment of environmental impact of wind farm construction

Activities associated with the installation of offshore wind turbines have the potential to affect marine mammals and seabirds, for example by displacing them from the area around construction sites. For construction consent, wind farm developers must undertake (costly) biological monitoring, and the resulting survey data must be analysed using methods that are capable of revealing construction-related effects. The Scottish Government commissioned Mackenzie and Scott-Hayward to create two freely available software packages, MRSea and MRSeaPower based around the CReSS spatial smoothing approach [R3, R4] which are designed to (a) quantify any windfarm related effects and (b) quantify the ability of the survey regime to detect these effects [S5]. The Renewables and Energy Programme Manager at Marine Scotland writes: "*MRSea is the recommended approach by both Natural England and Marine Scotland (2014-ongoing) and MRSea has been used for a wide range of wind farm installations to quantify impacts and any post-impact recovery and latterly MRSeaPower has been used to determine the adequacy of additional survey frequency subsequent to the identification of significant impacts.*" [S6]

To date, MRSea has been used in the consenting process and post-consent monitoring for at least 13 different farms in the UK and Denmark with a potential capacity of over 5450MW, enough to power over 4,500,000,000 homes. Denmark, at the forefront of wind power generation, had the first large scale offshore windfarm in the world (Horns Rev I) and in 2019 had the highest wind power generation in the world as a fraction of domestic consumption (47%). Use of MRSea is documented in reports underpinning the Evidence Plans and Environmental Statements as part of the consenting process for offshore wind farms. "*MRSea has been used in the process for several UK based [wind] farms (Lincs, Lyn and Inner Dowsing, Burbobank, Hornsea 3 and 4, Robin Rigg,Liverpool Bay and Moray West) and the very largest Danish windfarms (Rodsand I and II, and Horns Rev [I, II and II]). MRSeaPower has been used for the Lincs and Fehmarn Belt Fixed Link projects. This work is wide reaching and significant: the associated outputs inform both regulatory decision makers via the consent to operate, and industry by critically evaluating the frequency (and thus the substantial costs) of surveying.*" [S6]. The UK has a legal responsibility for protected species that can be affected by wind farms and so the beneficiaries include UK marine regulators by way of evidence-based decision making, windfarm-related companies (e.g., DONG and E.ON) and protected wildlife, such as the threatened red-throated diver (listed under Annex I of the EU Birds Directive) and harbour porpoise (listed in Annex I and IV of the EU Habitats Directive). MRSea has been used in windfarm-related impact assessment for both these vulnerable species, but also many more.

Deepwater Horizon oil spill environmental damage assessment

On April 20th, 2010, the Deepwater Horizon drilling unit exploded in the Northern Gulf of Mexico, resulting in the release of approximately 3,200,000,000 barrels of oil into Gulf waters. The US government NOAA began a Natural Resources Damage Assessment (NRDA), in preparation for a settlement or litigation against the legally responsible party, BP. One important component of the NRDA was the Marine Mammal Injury Quantification (MMIQ). In 2014, Thomas was invited to join the MMIQ team to assist in analysis of the multiple data-sources generated, and to help provide population projections under assumed baseline and impacted conditions [R5, R6, and others]. The team's report was submitted in 2015, and at about the same time, BP settled with the US government (and other stakeholders) for USD20,800,000,000, of which USD8,800,000,000 was assigned to restore the environmental damage. The chair of the MMIQ team and former Chief of the Oceans and Human Health Branch at NOAA writes "*Dr Thomas made significant contributions … as a leader in the development and implementation of innovative approaches for quantifying the marine mammal injury following the DWH oil spill. He and his colleagues at St Andrews were vital to the success of the injury quantification, which in turn was a key factor in the settlement with BP*." [S7] Regarding the ongoing impact of this work, they write: "*The quantification approaches that we developed [R6] … have provided a template for future marine mammal injury assessments. Our ground-breaking efforts have changed the way that NOAA approaches NRDAs. Previously reluctant to pursue marine mammal damages due to the difficulty in documenting and quantifying injuries, NOAA is now armed with robust analytical tools and the agency has made assessment of marine mammal injuries a high priority. … The innovative models and analytical approaches developed by our team [R5, R6] have prompted NOAA to more actively investigate and pursue damages for marine mammal injuries from oil and other chemical spills.*" [S7]

5. Sources to corroborate the impact

[S1] Department of the Navy. 2017. Technical report: Criteria and thresholds for U.S. Navy acoustic and explosive effects analysis (Phase III). SSC Pacific, San Diego, California, 194pp. https://tinyurl.com/r9ucah5 (Accessed 17/2/2020). R1 cited on pp.65-58, R2 cited on p.79.

[S2] Letter from Director of Energy and Environmental Readiness Division, Office of the Chief of Naval Operations, Department of the Navy, USA.

[S3] Letter from Chief of Staff, Royal Norwegian Navy.

[S4] Letter from Director of Department Maritime Systems, Royal Netherlands Navy.

[S5] Scottish government web page https://tinyurl.com/y3xyaxsq (accessed 29/1/2021) on MRSea and MRSeaPower.

[S6] Letter from Renewables and Energy Programme Manager, Marine Scotland.

[S7] Letter from Chair of Marine Mammal Injury Quantification Team and former Chief of the Oceans and Human Health Branch, NOAA.