Institution: University of the Highlands and Islands (UHI)		
Unit of Assessment: 7 Earth Systems and Environmental Science		
Title of case study: Protecting marine aquaculture and human health from the negative effects of harmful algal blooms		
Period when the underpinning research was undertaken: 2009 - present		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Keith Davidson	Professor	1998-present
Sarah Swan	Manager: Harmful Phytoplankton Monitoring Programme (HPMP)	1992-present
Callum Whyte	Deputy Manager HPMP & Research Scientist	2013-present
Dmitry Aleynik	Research Scientist	2009-present
Period when the claimed impact occurred: 2014 - 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Scotland's aquaculture industry, including both finfish and shellfish production, contributes ~£620 million a year to the Scottish economy, supports over 12,000 jobs, and generates employment in remote rural areas. UHI research has minimised the serious risks to the economic sustainability of the aquaculture industry and the health of consumers posed by harmful algal blooms (HABs) and their related biotoxins.

Specifically, understanding the development of HABs allows rapid reporting and forecasting of biotoxin-producing HABs. This allows shellfish producers and the regulatory body (Food Standards Scotland (FSS)) to suspend harvesting or undertake tests to verify the safety of the product when these HABs occur. Since 2014, this work and expertise has underpinned the safe supply of almost 15 million Scottish shellfish portions to UK and international consumers without a single reported poisoning case, and has saved the industry annual product recall costs of hundreds of thousands of pounds. The work has also informed HAB regulatory monitoring guidance produced for all EU member states.

In addition, forecasting HABs that are harmful to fish – known as ichthyotoxic HABs – directly benefits the finfish aquaculture industry. It also empowers the Scottish Environment Protection Agency (SEPA) and Marine Scotland (MS) to support Scottish aquaculture, enabling these organisations to maximise fish welfare and maintain the integrity and sustainable development of the industry.

2. Underpinning research

This research focuses on harmful algal blooms (HABs) and their toxins that are taken up and concentrated by commercially harvested shellfish, including mussels, scallops, and oysters. As well as posing a direct threat to human health (such poisoning can be fatal), this contamination has severe economic effects because it forces shellfish farms to close. Other HAB species can kill farmed fish, which also has significant economic impact.

The research has focused on understanding why, when, and where HABs arise, and how this knowledge can be leveraged to produce useful risk assessments and forecasts that give early warning of HABs and biotoxins to the aquaculture industry and its regulators. Led by Professor Davidson in the UHI partner The Scottish Association for Marine Science (SAMS), these studies have examined the ecology of HAB events and the conditions that contribute to development and oceanographic transport of the most important harmful algal genera in UK and other temperate waters: shellfish biotoxin producing *Alexandrium, Pseudo-nitzschia*, *Dinophysis,* and ichthyotoxic *Karenia*. Blooms are temporally and spatially variable and this research has used cell counts, toxin analysis, and oceanographic/meteorological measurements (currents, wind, temperature, tides etc.)

to develop a scientific understanding of HAB events in aquaculture production regions and has used this knowledge to build computer models of bloom development. The work has shown that different algal species react in different ways to environmental conditions. For example, shellfish biotoxin producing *Dinophysis* blooms tend to first develop at offshore frontal regions and be transported by water mass movements towards coastal aquaculture sites [3.1]. The work has also explained the factors that govern blooms of the harmful species *Karenia mikimotoi* that can cause significant farmed fish mortalities [3.2] and has evaluated how climate-driven changes in the environment have influenced the frequency and intensity of HABs in UK waters [3.3].

Many HABs are advective – transferred by the flow of the sea – developing offshore and being transported by oceanic currents before they cause harm on the coastline. UHI researchers have therefore developed particle tracking modelling approaches, based on high resolution unstructured grid techniques, to allow better prediction of the timing and location of harmful events in the complex, coastal, fjordic environments where aquaculture is typically located [3.4]. They have also developed and applied community index methodologies to evaluate how environmental factors such as anthropogenic nutrient loading influences the composition of the phytoplankton community and HAB events [3.5].

Taken together, these studies and other research from SAMS-UHI show that, while HABs and sustained increases in their biotoxins might seem to occur at random, a fuller understanding of the environmental conditions responsible for them and their ecology can in fact offer the understanding required to produce short-term forecasts of HAB and biotoxin risk [3.6].

UHI researchers in SAMS have also used their temporal/spatial understanding of HABs to develop statistical models that provide insight into where and when HABs and biotoxin risks are likely to be highest [3.7].

3. References to the research

Authors in **bold** conducted the underpinning case study research at UHI. # denotes senior author. *Authors in italics are also UHI academic staff, doctoral students, postdoctoral scientists, or technical staff.*

3.1. *Paterson RF, McNeill S, Mitchell E, Adams T*, **Swan S,** Clarke D, Miller PI, Bresnan E, **Davidson K#** (2017) Environmental control of harmful dinoflagellates and diatoms in a fjordic system. Harmful Algae 69:1-17

3.2**. Davidson K#**, Miller PI, *Wilding T*, Shutler J, Bresnan E, Kennington K, **Swan S** (2009) A large and prolonged bloom of *Karenia mikimotoi* in Scottish waters in 2006. Harmful Algae 8:349-361

3.3**.** *Dees P*, Bresnan E, *Dale A*, Edwards M, Johns D, *Mouat B*, **Whyte C**, **Davidson K#** (2017) Harmful algal blooms in the Eastern North Atlantic Ocean. Proceedings of the National Academy of Sciences 114 (46) E9763-E9764

3.4**. Aleynik D#**, *Dale AC, Porter M*, **Davidson K** (2016). A high resolution hydrodynamic model system suitable for novel harmful algal bloom modelling in areas of complex coastline and topography. Harmful Algae 53:102-117

3.5**. Whyte C#**, **Davidson K**, Gilpin L, *Mitchell E Moschonas G, McNeill S, Tett P* (2016). Tracking changes to a microplankton community in a Scottish sea loch using the micro-plankton index PI(mp). ICES J Marine Science. doi:10.1093/icesjms/fsw125

3.6**. Davidson K#**, Anderson DM, Mateus M, Reguera B, Silke J, Sourisseau M, Maguire J (2016) Forecasting the risk of harmful algal blooms: preface to the Asimuth special issue. Harmful Algae 53:1-7.

3.7. Holtrop G, **Swan S,** Duff B, *Wilding T, Narayanaswamy B,* **Davidson K#** (2016). Risk assessment of the Scottish monitoring programme for the marine biotoxins in shellfish harvested from classified production areas: review of the current sampling scheme to develop an improved programme based on evidence of risk. FSS/2015/021. 218pp.

Key Grants (all awarded to Prof. K. Davidson)
BBSRC/NERC: Evaluating the Environmental Conditions Required for the Development of Offshore Aquaculture (Off-Aqua). BB/S004246/1 (£710K, 2018-21)
NERC: Combining Autonomous observations & Models for Predicting and Understanding Shelf seas (CAMPUS). NE/R00675X/1 (£225K, 2018-21)
EU Atlantic Area Interreg: Predicting the impact of regional scale events on the aquaculture sector (PRIMROSE) (€310K, 2017-20)
BBSRC/NERC: Minimising the risk of harm to aquaculture and human health from advective harmful algal blooms. (Windy HABs). BB/M025934/1 (£250K, 2015-2017)
BBSRC/NERC: Satellite-based water quality bulletins for shellfish farms to support management decision (Shelleye) and its continuation Shelleye Demo (£500K, 2015-19)
Crown Estate: Synthesis and interpretation of data set relating to the harmful dinoflagellate *Karenia mikimotoi* in western Scottish waters (£57K, 2014-15)

4. Details of the impact

UHI research into HABs provides benefit for two main stakeholder groups: 1) the Scottish aquaculture industry and its consumers, through early warning systems, and 2) governmental regulators and policy makers for finfish and shellfish aquaculture in the UK and internationally.

4.1 Early warning/risk assessment of HABs & biotoxins for the aquaculture industry

The Scottish aquaculture industry produces more than 9,000 tonnes of shellfish each year, equating to three million portions consumed worldwide annually. Confidence in the aquaculture industry was damaged in 2013 when 70 people were poisoned by biotoxins generated by HABs in mussels harvested in Shetland and served in London restaurants. A direct impact of the post-2014 application of this research has been to minimise the potential for further human poisoning incidents in Scotland, the UK and elsewhere, with no reported human poisoning cases from algal biotoxins in Scottish shellfish since then.

To achieve this, the UHI team has deployed its research outputs to develop an early warning system that gives aquaculture companies notice of predicted HABs and biotoxin levels in the week ahead. After consultation with the trade groups Seafood Shetland and the Scottish Shellfish Marketing Group, in 2015 the SAMS group was funded by Seafood Shetland to produce weekly risk assessment bulletins for the Shetland Islands, an area that accounts for ~75% of national shellfish production. These bulletins are similar to weather forecasts, relying on research-based understanding of the environmental drivers of harmful blooms, mathematical models and individual research expertise to interpret the data and modelled predictions to produce a forecast risk assessment for the coming week. In 2016, the researchers extended this service to cover all of Scotland and moved to web dissemination via www.HABreports.org with the inclusion of mathematical model-based HAB predictions.

These risk assessment and forecast tools draw on the results of the research described above [3.1-3.6] and other SAMS work. They allow the industry to manage risk to their businesses and – as required of them as Food Business Operators – to human health, too. If levels of HABs or biotoxins are predicted to increase, shellfish harvesters can undertake precautionary end-product testing, move harvesting operations to another location, or cease harvesting temporarily altogether [5.1-5.2]. The predictions generated by the SAMS' models are also relevant to the finfish component of the industry: if fish killing species are forecast, businesses can deploy protective skirts or bubble curtains, modify feeding regimes, or move fish cage locations. The weekly risk assessment bulletins are sent to 57 recipients including 100% of Shetland's shellfish growers, the multi-national salmon producers Grieg Seafood and Scottish Sea Farms, and the Scottish Shellfish Marketing Group.
Ruth Henderson Chief Executive of Seafood Shetland states: "As HABs precede shellfish toxicity, early warning of their anticipated appearance permits our members in the shellfish industry to plan their harvesting operations in conjunction with their customers; this reduces the likelihood of human health incidents but also addresses business risk by allowing more informed husbandry and minimising expensive produce recalls. The financial saving of your early warning models and bulletins to the industry could therefore easily run into the £100s of thousands per

annum" [5.1]. Michael Tait, Chairman of the Scottish Shellfish Marketing Group, also says that the bulletins have "been of much use to the aquaculture industry in this region" and provided "a financial benefit to our business development" [5.2].

4.2a Regulatory monitoring: UK

Competent authorities in EU member states – including Food Standards Scotland (FSS) – monitor classified shellfish production areas in compliance with the EC regulation 854/2004, for the presence of biotoxin producing phytoplankton and the levels of biotoxins. It is not possible, logistically or financially, to monitor all shellfish harvesting sites at a high enough resolution to protect human health. As a result, FSS is obligated to make scientifically based decisions on the location and frequency of sampling of 'representative monitoring points', each of which is used as a sentinel site for a number of harvesting locations. Factors influencing this decision-making process include: the location of sites and their proximity to others, hydrography, historical HAB/biotoxin records, ecology of local HABs, and the shellfish species farmed. An overriding requirement is that the risk of not detecting biotoxins concentrations in shellfish flesh in excess of the maximum permissible level is below 1%. Using knowledge of HAB ecology and biotoxin chemistry, the UHI research was able to determine which organisms should be included within the monitoring programme [5.3] and allowed development of statistically-based mathematical models [3.7] that are now used by FSS to design the spatial distribution of the representative monitoring points within the programme to minimise health risk to consumers [5.4]. In 2014, this research was used by the UK National Reference Laboratory for Marine Biotoxins to set the regulatory threshold for both *Alexandrium* and *Pseudo-nitzschia* above which action is taken within the monitoring programme [5.5, item 2.2, pages 2-4]. UHI's research has therefore maximised the health protection provided by the programme within available resources.

Via SAMS' commercial arm (SRSL), UHI operates, under contract, the harmful phytoplankton monitoring component of the FSS regulatory shellfish safety monitoring programme outlined above. The team analyses water samples collected on a weekly basis from 40 monitoring sites around Scotland. Since 2014, the team has analysed (by August 2020) 9,788 samples and found 4,641 instances of dangerously high algal cell densities. FSS relies on UHI's research and subsequent expertise to interpret sometimes ambiguous results, by evaluating the magnitude of the risk from bloom events beyond the information provided by cell counts alone. For example, previous UHI research has shown the toxic diatom *Pseudo-nitzschia* is present in Scottish waters in either the more toxic 'seriata' group or less toxic 'delicatissima' group. SAMS is therefore able, on a day-to-day basis, to advise FSS on whether *Pseudo-nitzschia* blooms are high or low risk. In combination with toxicity data, FSS then allows or prohibits shellfish harvests accordingly. Dr Jacqui McElhiney, Head of Food Protection Science & Surveillance FSS, says: "SAMS particular scientific expertise has guided and supported the programme" and "enhanced risk assessment" [5.4].

This research has also directly influenced the way regulators and policy makers (the Scottish Environment Protection Agency (SEPA) and Marine Scotland (MS)) inform the public about HAB and biotoxin risks. In 2016, SAMS shared with SEPA its findings that a significant, so-called "red tide" bloom of the fish-killing dinoflagellate *Karenia mikimotoi* was developing in the Clyde Sea, together with a research-based interpretation of the likely cause and impact of this event. Pre-warned, SEPA was able to reassure the public that the subsequent observed mass marine faunal mortalities were not a direct result of any discharge from a regulated business or a human health concern [5.6].

MS also uses this research to support policy. For example, the research is important to MS's climate change advice adaptation plans [3.3, 5.7]. Dr. Eileen Bresnan of MS says: "These studies make an important contribution to Marine Scotland as they feed into the development and implementation of climate change adaptation plans for the aquaculture industry by the Scottish Government" [5.7]. Application of UHI's research through the HABreports web site also supports MS's ten-year Farmed Fish Health Strategy by providing both long term and real time information to improve the health and wellbeing of farmed fish and underpin the sustainable economic development of the industry. Dr. Bresnan also says: **"**Prof. Davidson's group provides the only mechanism which has already been successfully implemented in Scotland to provide this real time [HAB] information". "The development of the HABreports website by Prof. Davidson's group (https://www.habreports.org/), where the risk from [fish killing] *Karenia mikimotoi* blooms is evaluated and presented, represents a considerable resource to Marine Scotland. It allows the Marine Scotland Fish Health Inspectorate to provide the most up to date advice to the Scottish aquaculture industry" [5.7].

4.2b Regulatory monitoring: International

SAMS' research, and the subsequent expertise based on the results of this research, have also been used to set evidence-based, pan-European guidance on which harmful phytoplankton and biotoxins should be monitored and how this monitoring should be undertaken in the EU. In 2018, on the strength of his research and monitoring expertise, Prof. Davidson was invited to join a panel of seven experts asked to draw up a new technical guide on the principles of good practice in toxin-producing phytoplankton monitoring for the EU [5.8]. The guide is designed for use by the competent regulatory authorities in all EU member states to standardise their monitoring practices and embeds good practice established in Davidson's research e.g. [3.4 - 3.7]. Formal publication is awaiting agreement of all EU member states, the UK's adoption of the guide is confirmed by [5.9].

5. Sources to corroborate the impact

5.1. Letter from Ms. R. Henderson Chief Executive of Seafood Shetland (the major trade body for Shetland seafood) on benefits of UHI's risk assessments by the aquaculture industry.

5.2. Letter from Mr. M. Tait the Chief Executive of the Scottish Shellfish Marketing Group, (the leading sales organisation for farmed shellfish in the UK, responsible for ~ 80% of production) describing the use of the early warning risk assessments by his organization.

5.3. Report that was used by FSS to define which species and toxins are monitored in UK waters for Official Regulatory Control. Higman W., Turner A., Baker C., Higgins C., *Veszelovszki. A*, **Davidson K.** (2013) Research to support the development of a monitoring programme for new or emerging marine biotoxins in shellfish in UK waters. 437 pp.

5.4. Letter from Dr. J. McElhiney Head of Food Science and Surveillance, FSS corroborating the use of SAMS research within the official control monitoring programme.

5.5. Minutes of the UKNRL meeting for Maine Biotoxin 13th May 2014 at which the regulatory limit for *Alexandrium* and *Pseudo-nitzschia* used in Scottish Official Control monitoring was set based on SAMS research. Item 2, pages 2-4.

5.6. Letter from Dr. M. Baptie of SEPA that demonstrates the impact of SAMS-UHI's work on their public information activities.

5.7. Letter from Dr. E. Bresnan of Marine Scotland Science that demonstrates the impact of SAMS' research on MS's policy activities.

5.8. Letter from Dr. P. Serret of the EU National Reference Laboratory for Marine Biotoxins on the use of SAMS-UHI research in setting regulatory guidelines for all 28 EU states on regulatory harmful phytoplankton monitoring.

5.9. Letter from Ms. A. McKinney of the UK National Reference Laboratory for Marine Biotoxins on the use of SAMS-UHI research in setting regulatory guidelines for harmful phytoplankton monitoring in the UK.