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Applied simulations and integrated modelling for the understanding of toxic and harmful algal blooms (ASIMUTH): Integrated HAB forecast systems for Europe's Atlantic Arc

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ABSTRACT

Reasons for the emergent interest in HABs are abundant, including concerns associated with human health, adverse effects on biological resources, economic losses attributed to recreation, tourism and seafood related industries, and the cost of maintaining public advisory services and monitoring programs for shellfish toxins and water quality. The impact of HABs can potentially be mitigated by early warning of their development. In this regard the project ASIMUTH (Applied Simulations and Integrated Modelling for the Understanding of Toxic and Harmful algal blooms) was borne in order to develop short term HAB alert systems for Atlantic Europe. This was achieved using information on the most current marine conditions (weather, water characteristics, toxicity, harmful algal presence etc.) combined with high resolution local numerical predictions. This integrated, multidisciplinary, trans-boundary approach to the study of HABs developed during ASIMUTH led to a better understanding of the physical, chemical and ecological factors controlling these blooms, as well as their impact on human activities. The outcome was an appropriate alert system for an effective management of areas that are usually associated with HAB events and where these episodes may have a more significant negative impact on human activities. Specifically for the aquaculture industry, the information provided enabled farmers to adapt their working practices in time to prevent mortalities in finfish farms and/or manage their shellfish harvest more effectively. This paper summarises the modelling and alert developments generated by the ASIMUTH project.

1. ASIMUTH project concept and objectives

Harmful algal blooms act in two main ways: either they are directly toxic to marine life or humans, or they produce toxins that are concentrated in intermediate consumers such as shellfish, of which subsequent consumption by humans can lead to serious illness and, on occasion, can be fatal. Harmful toxic phytoplankton that historically have caused mortalities of cultured finfish or prolonged closures of shellfisheries in the Atlantic sub-regions were targeted by each partner. In our area of interest, targeted harmful phytoplankton species include the high biomass forming fish killing dinoflagellate *Karenia mikimotoi* and the potentially toxic genera (e.g. *Dinophysis* spp. *Pseudo-nitzschia* spp. and *Alexandrium* spp.) that produce biotoxins harmful to humans when consumed; typically through the vector of biotoxin contaminated shellfish.

HABs can therefore lead to the loss of stock, which have been estimated globally to be in the order of €200 million in one year. Those events that lead to illness in humans are estimated to give rise to losses in excess of €75 million per year (Anderson et al., 2000; Hoagland et al., 2002; Hoagland and Scatasta, 2006; Lu and Hodgkiss, 2004). Understanding the occurrence and movement of HABs is therefore a key commercial/economic factor in marine aquaculture enterprises and in certain marine leisure activities. Planning activities to minimize the commercial impact of HABs has the potential to save large sums of money for these operators.

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HABs result in economic losses in coastal areas of the North East Atlantic. The countries that make up this region have unique and shared HAB problems in terms of the organisms involved and their impact on wild and natural fisheries, shellfish toxicity and human health. Monitoring programmes for HABs are established in ASIMUTH countries to protect public health and control fish quality. Given that HAB events do not respect national boundaries (e.g. Díaz et al., 2016; Moita et al., 2016), cross region networking and scientific development are required to achieve early HAB warning and improved management strategies. To this end a consortium of organizations (11 in total) from Portugal, Spain, France, Ireland and Scotland formed the ASIMUTH project with the aim of applying state of the art modelling and forecasting technologies to provide high value information to aquaculturists and other water users. The partnership developed linkages between physical and biological scientists working in the field of HABs and allowed collaboration between agencies that seek to use novel means of detection and description of HABs (including modelling, remote sensing, and monitoring) for the management of their impacts.

2. Background to development

Over the past few years there has been much discussion on the use of satellite remote sensing for tracking surface algal blooms. For example the EU Copernicus Marine Environmental Monitoring Service (http://marine.copernicus.eu, formerly called Marine Core Service) has increased the availability and accessibility of satellite remotely sensed ocean chlorophyll data. This has resulted in the production of some services that purport to be HAB nowcasts and forecasts. Though there is merit in using satellite derived chlorophyll images to delineate high biomass near surface algal blooms, understanding biological phenomena in the ocean requires a multi parameter approach, particularly for toxin producing organisms that rarely dominate the phytoplankton biomass. For example, recent studies have demonstrated that some HAB species can be present in thin (potentially <1 m in thickness) layers of limited geographical extent often associated with strong density interfaces in the water column, and at a depth that are not detectable by remote sensing.

Chlorophyll data derived from satellites, while important, is not sufficient on its own to allow HAB detection. Yet when used in combination with other operational oceanographic or meteorological in-situ and/or modelled products such as sea surface temperature (Gillibrand et al., 2016; Díaz et al., 2016), wind fields and/or other relevant high frequency data streams such as national HAB and biotoxin monitoring data, a more holistic picture of HAB risk can be obtained.

Historically the use of mathematical models in HAB forecasting has been limited by both physical and biological constraints. Shelf wide physical oceanographic models often lacked the necessary spatial resolution of model grid to resolve the complexities of the near coast environments where aquaculture is located, with the physiology of many HAB organisms being insufficiently understood to produce credible operational biological models, particularly if they exist as a minor component of the biomass of a complex food web including processes such as mixotrophy. While the development of biologically based operational HAB models remains a major challenge, even for high biomass blooms, physical models have developed such that robust operational models exist for most shelf seas, including those within the ASIMUTH domain. The use of such models to simulate the Lagrangian transport of known HABs provides a further potential mechanism for HAB early warning.

The combined used of mathematical model forecasts, satellite imagery and in-situ networks supplied by the Copernicus Marine Environment Monitoring Service and intermediate users, along with an array of biological samples collected from regulatory and other HAB and biotoxin monitoring programmes, provided sufficient scope to allow the production of worthwhile HAB forecasting downstream services to the aquaculture industry. Using such an approach the ASIMUTH project has developed the first realistic HAB forecasting capability as a Copernicus (formerly called GMES or Global Monitoring for Environment and Security) downstream service to users, in this case the European aquaculture industry along Europe's Atlantic Margin. An important component of these forecasts was the expert interpretation provided by HAB biology experts through the synthesis of the different data streams to give overall HAB risk to aquaculture.

3. Key developments during ASIMUTH

1. Operational HAB model forecast systems/bulletins were developed to predict and track the regional distribution of selected phytoplankton species considered harmful and/or toxic to finfish/shellfish produced commercially by aquaculture industry in the partner countries.
2. Mathematical models formed an important component of these alerts. To facilitate this, national and regional hydrodynamic models were to be used to forecast the alongshore and onshore movement of HABs. An important part of the process was the exchange of information (computer scripts, methodologies, boundary conditions, HAB alert initiated between sub-regions when passive particles enter a neighbour's domain etc.) between partners in each EU member state.
3. ASIMUTH forecasts allowed the combination of Copernicus downstream services (providing open boundary conditions for coastal models as well as satellite and in-situ data) with national HAB and biotoxin monitoring and mathematical models to be synthesized in regional or national format (ASIMUTH bulletins) for the benefit of the aquaculture industry. Effort was also invested in exchanging data from different national HAB monitoring programs and in displaying them in a common viewer for assessing bloom initiation and subsequent transport to adjacent areas monitored by a different national program.
4. Operational systems operated weekly during the summer of 2013 as a part of the project as a proof of concept, with a number continuing to operate post project (for example the Irish bulletin can be found at http://www.marine.ie/Home/site-area/data-services/interactive-maps/weekly-hab-bulletin and the Scottish bulletin at http://www.somuchtosea.co.uk/news/bulletin_for_shellfish_farmers.aspx).

4. Summary of the contents of the special issue

Briefly outlined below are the experimental results, model developments and validation exercises which facilitated the development of forecasts and eventually the products delivered to the user in each targeted Atlantic sub-region (Portugal, Spain, France, Ireland and Scotland). Close collaboration between partners was considered important. For example, the Irish model was used to define the boundary conditions of the Scottish model. Furthermore, model development and maintenance typically involves a large commitment and investment of resources (people and access to high performance computers) at national and European level. Hydrodynamic models were already in place as part of national modelling initiatives for all countries and were extended to include a new HAB functionality. Models provided information on the variability of hydrodynamical properties (temperature, salinity, currents) as well as on the variability of ecological properties like chlorophyll and nutrients.

Some studies used long time series (Moita et al., 2016; Díaz et al., 2016) to investigate and test models of the relationship between blooms and oceanographic events, or the analysis of specific exceptional blooms (Gillibrand et al., 2016). Specific high resolutions models were developed in some key aquaculture locations (Bantry Bay Ireland: Dabrowski et al., 2016; and the Argyll region of the Scottish West coast: Aleynik et al., 2016) on the basis of specific hydrodynamics (Ireland) or complicated topography of the target region that required an unstructured grid approach to resolve (Scotland). Both studies highlighted the importance of having realistic models, including local winds, surface forcing. Subsequent validation indicated that the models were capable of capturing physical phenomena that preceded HAB events, for example a downwelling episode prior to the arrival of a *Dinophysis* bloom in Bantry Bay (Cusack et al., 2016). Finally, some studies were conducted to better understand the physiology or biogeography of key organisms, e.g. Eckford-Soper et al. (2016) studied the competitive interaction of toxic and non-toxic *Alexandrium tamarense* from Scottish waters, and the use of specific remote sensing approaches in conjunction with coastal monitoring and boat based field work to understand the dynamics of two high biomass species, *Karenia mikimotoi* and *Lepidodinium chlorophorum*, in French waters (Sourisseau et al., 2016). Impacts of blooms were also assessed, for example O'Boyle et al. (2016) evaluated the impact of oxygen depletion associated with high biomass *K. mikimotoi* blooms in Ireland.

During ASIMUTH, satellite imagery has been evaluated in the context of HAB early warning. Satellite derived chlorophyll images have merit to delineate high biomass near surface algal blooms. Sourisseau et al. (2016) present satellite indexes based on the remote-sensing reflectances at six channels to track high biomass dinoflagellate blooms of *Karenia mikimotoi* and *Lepidodinium chlorophorum*. Satellite imagery has been used to follow *Karenia* blooms analyzed during ASIMUTH (Gillibrand et al., 2016). Other dinoflagellate species causing HABs in the European Atlantic area like *Dinophysis* spp. cannot be detected directly in satellite imagery because they usually appear in subsurface blooms. Additionally, they appear in low densities (<10^3 cells l^{-1}), which comprise a small proportion of the microphytoplankton. For low biomass species like *Dinophysis* initiation of a bloom is considered when quantitative methods start detecting its presence. Therefore, bloom initiation of low-biomass species, such as *Dinophysis* species, cannot be assessed directly by numerical models nor by satellite imagery. Once the presence of low biomass is detected by the monitoring system, the analysis of in-situ and satellite data combined with model forecasts of oceanographic conditions can help assess the risk of transport of cells to adjacent areas (Pinto et al., 2016; Ruiz-Villarreal et al., 2016).

When developing mathematical models both Eulerian and Lagrangian approaches were considered in ASIMUTH. All partners developed a capability for predicting the transport of observed HAB events based on Lagrangian particle tracking that have previously been shown to be successful in tracking HAB populations in the wild. The advantages are that they can be quickly used within an alert system to track movement of identified HABs between coastal areas in close proximity over short timescales, with models being easily run "off-line" on saved hydrodynamic fields, typically at time interval of c. 1 h.

By using the national hydrodynamic operational forecasting models, that routinely undergo strict validation procedures, good confidence existed in the predicted transport processes and the Lagrangian approach typically provided a reliable and fast

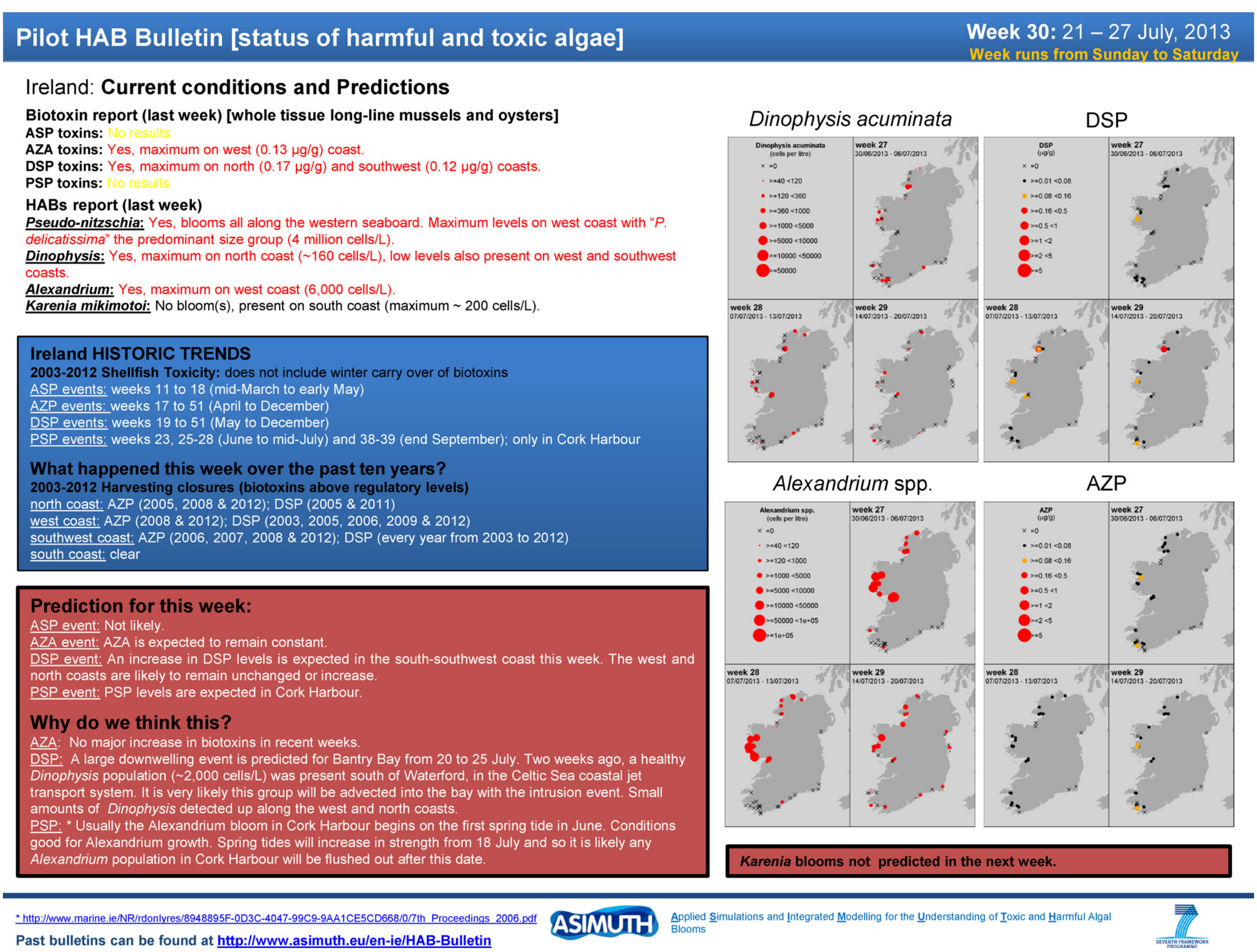


Fig. 1. Selected pages of a HAB forecast bulletin from Ireland (July 2013).

Pilot HAB Bulletin [status of harmful and toxic algae]

Week 30: 21 – 27 July, 2013
Week runs from Sunday to Saturday

Phytoplankton general observations (last week):

Phytoplankton are in full bloom.

Region	Predominant Phytoplankton
northwest-north:	**Microflagellates** (~10 million cells/L) and **diatoms** (e.g. "*P. delicatissima" group & Leptocylindrus minimus*) Highest dinoflagellate counts represented by *Alexandrium* spp. (2,500 cells/L)
west:	**Diatoms** ("*Pseudo-nitzschia delicatissima*" size group ~ 4 million cells/L; *Chaetoceros* spp. ~ 0.5 million cells/L; *Leptocylindrus minimus* ~400,000 cells/L etc.). Highest dinoflagellate counts represented by Azadinium / *Heterocapsa* spp. (8,000 cells/L)
southwest:	**Diatoms** (*Chaetoceros* spp. ~400,000 cells/L; ("*P. delicatissima*" size group >100,000 cells/L) and the **dinoflagellate** *Prorocentrum micans* (150,000 cells/L).
south:	**Microflagellates** (90,000 cells/L), **diatoms** (e.g. *Chaetoceros* spp. ~10,000 cells/L) and low levels of **dinoflagellates** (*Prorocentrum micans* 2,000 cells/L)
east-southeast:	**Assorted diatoms** (*Chaetoceros* spp. ~ 0.5 million cells/L; *Lauderia / Detonula* spp. ~350,000 cells/L) and Euglenoids (~300,000 cells/L)

Comments:

Surface chlorophyll levels have declined on the east coast with the collapse of the *Phaeocystis* bloom replaced by diatoms and euglenoids.

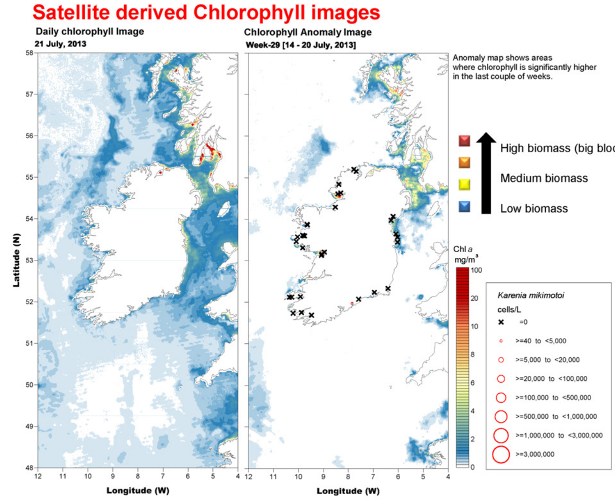
A microflagellate bloom on north coast has doubled in size since last week.

A *Pseudo-nitzschia* bloom is present on the west coast.

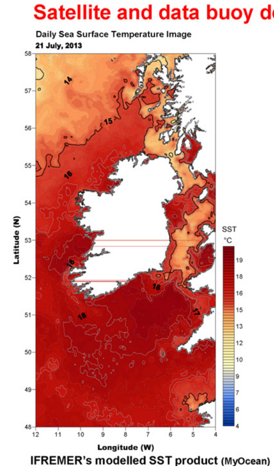
Elevated chlorophyll levels present in offshore waters on northwest coast –phytoplankton assemblage likely to be diatoms based on inshore station results.

20 July 2013
Northwest coast Ireland
NASA (Modis Aqua)

Satellite derived Chlorophyll images



Satellite and data buoy derived Sea Surface Temperature (SST)



SST (ºC) anomaly:
Data taken from the Irish data buoy network where the anomaly is the weekly difference in SST compared to the long term mean (~ 10 yrs)

Celtic Sea (M5) above average by plus 2.1 ºC
SST 15 July = 18.1 ºC; SST 23 July = 17.8 ºC;

Southwest coast (M3) *offline*

Northwest coast (M4) above average by plus 0.2 ºC;
SST 15 July = 14.9 ºC; SST 23 July = 17.3 ºC

Fig. 1. (*Continued*).

short-term forecast of the physical displacement of particles that represent identified potential HAB events and enabled the observational system to focus on specific target areas.

Stumpf et al. (2009) described the validation of HAB forecast tools and evaluate their skill in predicting transport, intensification, and extent. The skill of the ASIMUTH forecast system has been evaluated with data on the occurrence of HAB events obtained by the monitoring systems in the different regions. The ASIMUTH forecast system showed skill in predicting transport of HABs and in assessing the area affected by a HAB. The ASIMUTH system provided information on the variability of cross-shore and along-shore flows that move HAB populations towards (or away from) harvesting places. Along-shore transport is well described and has been forecast by the ASIMUTH system. As an example, the northwards along-shore transport of *Dinophysis acuta* populations in several autumn periods on the western Iberian coast is well represented (Ruiz-Villarreal et al., 2016; Moita et al., 2016). An example of shelf edge transport is the description of the northwards transport during summer 2006 of *Karenia mikimotoi* source population by the Hebridean slope current (Gillibrand et al., 2016). Pinto et al. (2016) simulate the along-shore transport and dispersion of five HAB events of different species in the Portuguese area following bloom detection. The entrance of HAB populations into coastal embayments, estuaries, rias, beaches, where cultures take place, varies in response to variations in tides and meteorological events, which can only be properly accounted for with a numerical model. HAB forecasts based on hydrodynamical and particle tracking models have shown skill in describing and predicting flows in and out of harvesting areas and their variability in Ireland, Galicia and Scotland (Cusack et al., 2016; Ruiz-Villarreal et al., 2016; Aleynik et al., 2016).

As demonstrated by the sensitivity analysis of Gillibrand et al. (2016), improved prediction of HAB events requires physiologically based biological models capable of capturing both the growth and death phases of blooms and their response to environmental forcing. A clear conclusion from the project is therefore that one of the main constraints on further progress in model based HAB early warning is a lack of knowledge (and hence ability to parameterize models) on many aspects of HAB biological behaviour e.g. sexual reproduction, cell death and resting life cycle stages. Even if robust biological models were available, when run operationally (e.g. online) they are much more computationally expensive, and hence slower, than Lagrangian models. Further development of operational HAB modelling will therefore require not only increases in biological understanding but also in the computation power necessary to exploit them in the appropriate timescales to allow early warning of HABs.

4.1. Risk assessment bulletins

During the demonstration period, the results of the ASIMUTH forecast system together with in-situ data of location and concentration of HAB species and toxins from the national monitoring program was disseminated in all ASIMUTH regions in the format of a bulletin issued on a weekly basis. The bulletin gave information on the location, extent and potential for development or movement of harmful algal blooms and associated biotoxins. Bulletins were disseminated to end users from monitoring agencies and the aquaculture sector and their requirements have been taken into account for the restructuring of bulletins better suited presentation of data and forecasts. The manuscripts of Pinto et al. (2016) and Ruiz-Villarreal et al. (2016) demonstrate the complementary use of modelling and other data streams (satellite data, in-situ data from HAB monitoring programs) to produce national HAB risk assessment bulletins in Portugal and Spain, respectively. Example pages from the assessment bulletins from Ireland are presented in Fig. 1, demonstrating the current conditions and predictions for ASP, AZA, DSP and PSP for the 21–27th July 2013. Fig. 2 shows an example page from a bulletin during a *Karenia mikimotoi* outbreak in Scotland in October 2013.

The fact that not all HAB forecast bulletins are operational to date illustrates the difficulties of moving from research and development to operations. Operational routine services do not only rely on a prototype that has shown utility and skill, but also rely on the availability of specific budget and human resources to maintain the operating system in place.

In the weekly bulletins the experts produced, probabilities of occurrence were assigned. During ASIMUTH, assessment of the predictions of different bulletins was carried out to compare the predicted conditions to the actual chemical results of toxins in different regions. Silva et al. (2016) present an assessment of the forecast accuracy of Portuguese bulletins. The Portuguese bulletin reports weekly the current status (open/close) and issues a forecast (open, trend to open, trend to close, close) for biotoxins and phytoplankton concentrations by shellfish production and harvesting area. The score was computed considering the number of forecasts that were verified to be correct the following week (85%) as well as the number of events not forecast (false negatives, 12%) and those expected but did not occur (false positives, 3%). The HAB prediction assessment of the Irish bulletins was carried out by an independent party not involved in the production of the HAB bulletins. While the Portuguese assessment was based on the forecast of the status of harvesting areas (open/close), in the Irish assessment a score was assigned based on whether the maximum level of the biotoxin recorded, was above or below 50% of the legal limit. In Table 1 the rules for assignment of the scores are summarized. The final score for each week (Table 2) was averaged and the overall result was that the biotoxin prediction was successful ~80% of the time.

5. Key benefits

The major benefit of this project is a forecasting system for HABs which allows improved knowledge based decision-making for the sustainable use of marine fish and shellfish resources. Engagement with key governmental and non-governmental groups led to the development of participatory warning systems

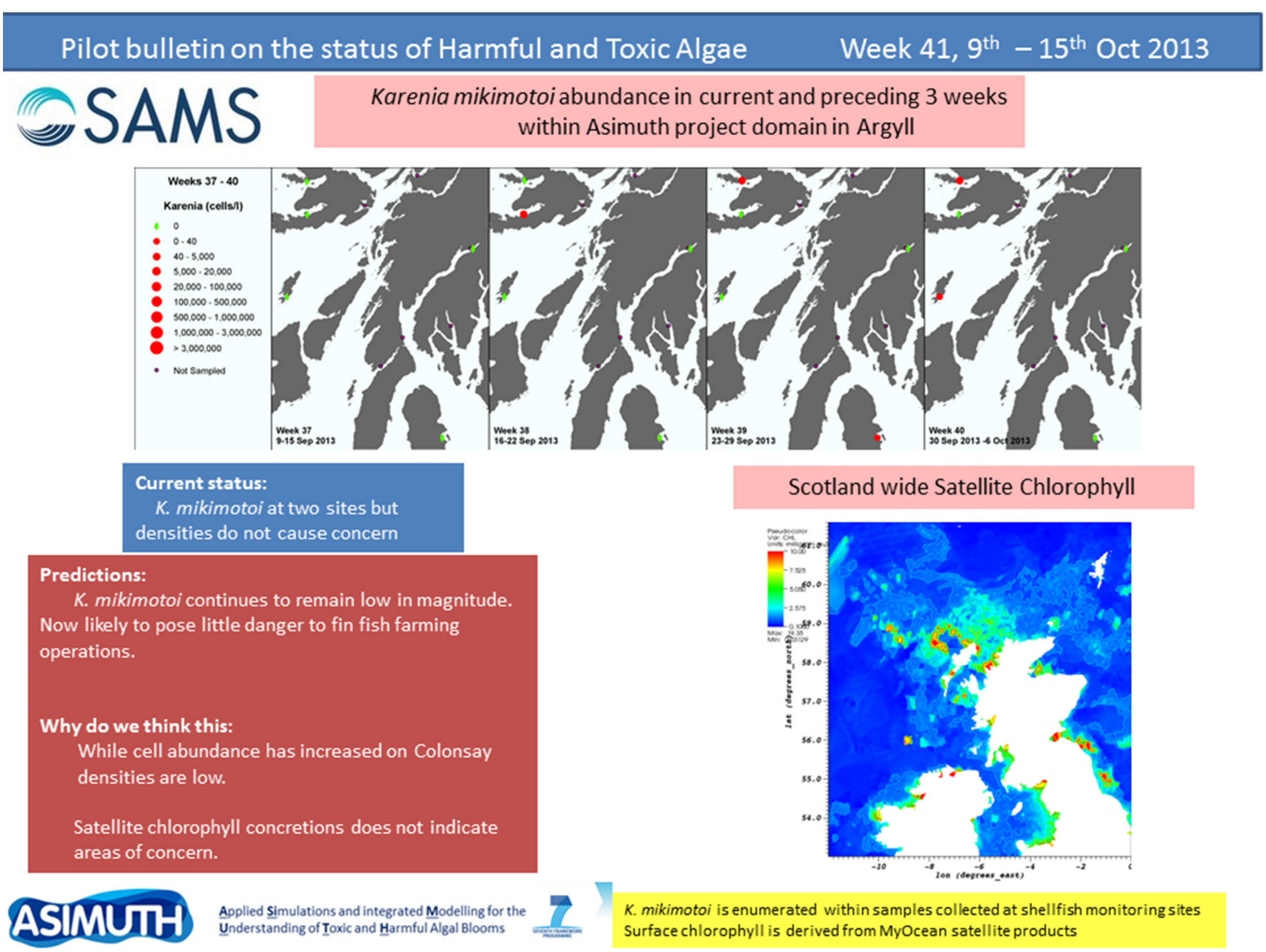


Fig. 2. Selected pages of a HAB forecast bulletin from Scotland during a *Karenia mikimotoi* outbreak in October 2013.

Table 1
Rules related to the score given to the weekly prediction of each biotoxin (ASP, AZP, DSP and PSP). The score given is based on the actual chemistry results after the prediction was made.

Predict	Actual chemistry	Score
Y	Y	5
Y	N	2
N	Y	1
N	N	5
N	Y (≤50% of legal limit)	3
N	Y (≥49% of legal limit)	2
Y	Y (≥50% of legal limit)	4
Y	Y (≤49% of legal limit)	3
Stay same	Stay same	5
Stay same	Y (≤50% change from previous, unless it becomes an event)	4
Stay same	Y (≥49% change from previous, unless it becomes an event)	3
Stay same	Y	2

Y = event predicted/biotoxin levels recorded, N = event not predicted/biotoxin levels not recorded.

Table 2
Scores of the assessment of the Irish bulletins during the ASIMUTH demonstration period.

Week	ASP event	AZA event	DSP event	PSP event	Weekly score
21	4.00				
22	5.00				
23	3.00	3.00	5.00		5.00
24	3.00	2.00	3.00	5.00	
25	5.00	1.00	3.00	3.00	
26	4.00	3.00	4.00	3.00	
27	5.00	5.00	3.00	3.00	
28	5.00	3.00	3.00	5.00	
29	5.00	4.00	3.00		
30	5.00	2.00	1.00	5.00	
31	5.00	2.00	2.00	5.00	
32					
33					
34	5.00	4.00	5.00	5.00	
35	5.00	5.00	4.00	5.00	
36	5.00	5.00	4.00	5.00	
37	5.00	5.00	5.00	5.00	

and subsequent management tools and their consideration for practical implementation for farms, coastal zone management and conservation authorities.

Given the low cost margins of the aquaculture industry it is vital that risk assessments are low cost and easily applicable, and hence utilise existing high frequency open access data products. Fish and shellfish farmers gain fore-warning of severe blooms which will enable them to adapt their husbandry practices to cope with stressful events in harmony with the surrounding environment. Therefore it is envisaged that the use of such new tools and strategies by SMEs will lead to the practical implementation of the project results.

For shellfish farming there are no current strategies used to avoid HABs. Bays simply close for harvesting and farmers are left to wait until the bay re-opens before they can harvest again. Sometimes closures can last for many months. As mentioned earlier, production losses then occur from prolonged bay closures because the fully grown shellfish (particularly mussels) can become too heavy for their growing structures and will eventually fall off particularly during winter storms. If an early warning system were available production schedules could be adapted to suit each HAB situation. At the moment no such option is available to shellfish farmers.

For finfish farmers, oxygen depletion in sea cages during an algal bloom event (particularly at night) is a major problem throughout the European and global aquaculture industries. Compressors in particular cannot stay at sea indefinitely as they are not built to withstand sea conditions in the long term, aeration systems are also very expensive and take time to install. Sometimes they are placed at sea when it is already too late. If a warning system was in place the farmers would have time to install systems properly or even be able to tow cages away from the bloom.

In terms of market challenges the aquaculture sector has been and will be increasingly exposed to international competition in the fish and shellfish sectors, competition is particularly strong from Asia (China and Japan), South America (particularly Chile), New Zealand and America (Canada and US). The development of a warning system for algal blooms and subsequent increased productivity of fish and shellfish through improved management practices would have the potential to increase the supply and eliminate price fluctuations for raw material currently experienced by producers. Thus by sharing the knowledge transferred, the sector would be in a better position to tackle increasing international competition. It is difficult to quantify the potential impact of the warning system and improved practices in absolute monetary terms but we expect that productivity can increase by optimising harvesting schedules and installing appropriate aeration systems. Therefore the long term aim of the project was: The creation of a financially self-sustainable forecasting system in Scotland, Ireland, France, Spain and Portugal and through ASIMUTH we have gone a long way to achieving this goal.

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