Independent Expert Assessment of Unusual Crustacean Mortality in the North-east of England in 2021 and 2022

Compiled by a panel of independent experts convened by Defra's Chief Scientific Adviser

17 January 2023

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This report documents the findings of an expert panel convened to consider the unusual mass mortality of crustaceans in the north-east of England starting in autumn 2021.

The panel was chaired by the Chief Scientific Adviser (CSA) of the Department for Environment, Food and Rural Affairs (Defra), Professor Gideon Henderson, with input from the Government CSA (GCSA) Professor, Sir Patrick Vallance. The crustacean mortality expert panel (CMEP) consisted of experts from academia and industry with a range of knowledge and experience spanning crustacean biology, marine eco-toxicology, sea-life histology/pathology, marine pollutants, algal blooms, chemical dispersion in the oceans, sediment and water chemistry, dredging, and coastal processes. The full CMEP met on three occasions between December 2022 and January 2023, with subgroups meeting to analyse aspects of the issue between meetings. The CMEP was tasked with providing an independent scientific assessment of all the possible causes of the mass crustacean mortality incident using all the relevant available data. The CMEP's remit did not extend to consideration of government processes during the investigation of the mortality event(s), to food safety, nor to the economic implications of the deaths. This report represents the consensus views of the CMEP, has been produced by the CSA's Office, and reviewed by the GCSA.

Membership of CMEP:

Gideon Henderson – Defra Chief Scientific Adviser
Eileen Bresnan – Marine Scotland
Jan Brooke – Environmental consultant
Keith Davidson – Scottish Association for Marine Science (SAMS)
Mike Dearnaley – HR Wallingford
Mark Fitzsimons – University of Plymouth
Alex Ford – University of Portsmouth
Tamara Galloway – University of Exeter
Crispin Halsall – University of Lancaster
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Executive summary

An unusually large number of dead or dying crustaceans started to be found along the coast of the north-east of England from early October 2021. This unusual mortality continued through October and November 2021, and continued periodically through 2022 (although it is difficult to distinguish reporting bias due to increased awareness). Crustacean wash-ups were found along at least 70 km of coastline, and dead or dying crustaceans were also reported by fishers over a wide region.

Some of these crustaceans displayed a twitching behaviour not normally observed in beach wash-ups, or during fishing activity. This unusual twitching was particularly apparent during the initial period of mortality (October to November 2021) and again during May 2022, and was observed along at least 70 km of the coastline.

Initial unusual wash-ups were dominated by crabs. There have been reports of a number of other species found dead on beaches in the area, but it is unclear these are more frequent than normal occurrences, with the possible exception of a large number of octopuses on one occasion.

The cause of this unusual crustacean mortality event has been controversial, with two prevailing theories being considered most closely: a harmful algal bloom, and toxicity from pyridine released by local dredging activity.

The Crustacean Mortality Expert Panel (CMEP) was convened in December 2022 to provide an independent scientific assessment of all the possible causes of the mass crustacean mortality incident using all relevant available data. The panel considered possible causes (including but not limited to the two previously dominant theories) and grouped their consideration into four sections: disease pathology, harmful algal bloom, chemical toxicity, and dredging.

Each potential cause was assessed for likelihood, as defined by the Intergovernmental Panel of Climate Change (IPCC) likelihood scale (*italics* are used to denote use of this scale).

Table 1: IPCC likelihood terminology.

Terminology	Likelihood of the occurrence/outcome
Virtually certain	>99% probability of occurrence
Very likely	>90% probability
Likely	>66% probability
About as likely as not	33 to 66% probability
Unlikely	<33% probability
Very unlikely	<10% probability
Exceptionally unlikely	<1% probability

Disease pathology: The panel considered whether the mortalities could be caused by disease or parasites. There are pathogens that are known to cause similar symptoms to those observed in the north-east of England, including the unusual twitching behaviour. Such pathogens have caused mortality events and declines in crustacean populations around the world. An amoebic crustacean disease, belonging to a similar group of parasites causing mortalities in the USA, has recently been found for the first time in UK waters in crabs on the south coast. No significant pathogens were identified in the north-east crabs, but full molecular screening was not conducted. The panel consider it is ***about as likely as not***, **that a pathogen new to UK waters caused the unusual crustacean mortality**.

Harmful algal bloom (HAB): Coastal waters can, under certain conditions, experience a bloom of particular taxa that cause harm to the marine ecosystem or species. These harmful algal blooms (HABs) can cause mortality due to release of toxins from the algae in the bloom, or because they lead to depletion of oxygen in the water.

The expert panel assessed satellite data and water-column measurements and concluded that the presence of an algal bloom in the area during September 2021 was *likely*. The intensity and duration of this bloom is uncertain, but it is *unlikely* that the bloom persisted beyond a storm in early October 2021.

Karenia mikimotoi is the most likely species to cause mortalities of benthic organisms by an algal toxin in UK waters. There is some evidence for the presence of this species in the month before the mortality events, but a lack of measurements at the time and location of the mortality events prevent assessment of the role of algal toxins. The impacts of algal toxins are relatively indiscriminate and it would be anticipated that a widespread mortality of a broad range of organisms would also have been reported. This lack of evidence, and particularly the continuation of mortality beyond the time when a HAB is likely to be present, make it ***unlikely* that a HAB toxin caused the unusual crustacean mortality**.

As the algae die oxygen levels in the benthic zone where crustaceans reside can decrease. Such conditions generally impact multiple bottom-dwelling species, but there is evidence that crustaceans are particularly vulnerable to lowering oxygen levels. Anoxia may therefore contribute to the unusual mortality of crustaceans, particularly in October 2021, but the panel could find no published evidence that low oxygen led to the twitching behaviour observed in some crabs, and mortalities of a more widespread range of taxa is normally seen during anoxia. These facts, along with the continuation of crab deaths for some time after the HAB is likely to be present, led the panel to consider it ***unlikely* that anoxia associated with a HAB caused the unusual crustacean mortality**.

Chemical toxicity (including pyridine) from shore-based sources and sediment

Teesside has a history of industrial activity, including a range of activities that have generated toxic chemical substances. These include pyridine which is known to be toxic to crabs at concentrations of around 10 mg/litre.

There is evidence of historical production of pyridine on Teesside associated with industries including chemical production and steelworks. The panel considered these industries, including their waste disposal and demolition, and concluded that they could not be sources of any significant volume of pyridine during the period of crustacean mortality. Measurements of seawater by the Environment Agency and by York University, including but not limited to those during the incident period, could not detect pyridine, which supports this conclusion. Previous modelling of the dispersion of pyridine from a potential Tees source was considered by the panel. This modelling is based on release of a very large volume of pyridine but, even with this release, pyridine concentrations remain significantly below the level required for crab mortality. In the absence of any significant source of pyridine, the panel concluded that it is ***very unlikely* that a point source of pyridine in Teesside caused the unusual crustacean mortality**.

Sediment measurements of pyridine, combined with assessment of the character and volumes of dredged material, indicate that the maximum pyridine release from sediment during dredging is several orders of magnitude lower than required to lead to water-column concentrations sufficient for crab mortality. The panel concluded that it is ***very unlikely* that pyridine release from sediments led to toxicity and mortality for crabs.**

A range of other toxic chemicals, including persistent organic pollutants, heavy metals, and tri-butyl-tin are found in sediments in the Tees and are the result of long-term industrial activity in the region. These pollutants are measured and reported as part of usual regulated activities such as dredging and disposal. Measurements in the Tees region and existing knowledge about dispersion and behaviour of these pollutants and their toxicity enabled the panel to conclude that is ***very unlikely* that a toxic pollutant other than pyridine caused the unusual crustacean mortality**.

Widely used chemicals such as pharmaceuticals and pesticides can enter seawater through normal river flow or from waste-water treatment. Although there is evidence for association of initial mortality with a period of sewage discharge, a suite of chemical measurements in waters, and the absence of any reason to expect the north-east of England to have greater fluxes of these chemicals than other parts of the UK, led the panel to conclude that it is ***very unlikely*** **that chemicals associated with run-off from shore caused the unusual crustacean mortality.**

Dredging

In dynamic estuaries and coastal areas, many ports and harbours need to dredge to provide and maintain safe navigable depths. Capital dredging excavates geological or historically accumulated sediments to create a new or deeper channel or berth. Maintenance dredging removes recent infill material to provide safe operating conditions in the context of the original or 'declared' channel (or berth) depth.

No capital dredging was undertaken in the Tees area in the period before or during the unusual mortality event. The last capital dredging before this period was in December 2020, and the new capital dredging at Teesworks did not commence until September 2022. The panel therefore considers it ***exceptionally unlikely*** **that capital dredging on the Tees caused the unusual crustacean mortality seen in this region between these dates**.

A larger than normal dredger was operating in the channel offshore Teesside during late September and early October 2021. The vessel was dredging recently mobilised sandy material deposited in the channel by storm events. Although larger than normal volumes of sediment were mobilised, maximum possible release of toxic chemicals, including pyridine, is significantly too small to cause crab mortality. Other routine dredging was also underway in the Tees Estuary by the port's dredgers. This was similar to activity conducted every month to keep the port operational and followed normal regulatory procedures. Considering all available evidence about Teesside dredging the panel considers it ***very unlikely*** **that release of any toxic chemical, including pyridine, due to maintenance dredging could have caused the deaths**. This conclusion is supported by the broad geographic spread and long duration of crustacean mortality.

Summary

Overall, the panel was unable to identify a clear and convincing single cause for the unusual crustacean mortality. The key observations that any cause must be capable of explaining are:

- Mortality over a sustained period and along at least 70 km of coastline;
- The unusual twitching observed by dying crabs in many locations
- The dominant mortality of crustaceans rather than a wider range of species

A novel pathogen is considered the most likely cause of mortality (despite the lack of direct evidence of such a pathogen), because it would explain these key observations. The impact of an algal bloom would also explain the wide distribution of observed deaths and cannot be ruled out as a causative factor particularly early in the incident. It is unlikely, however, that an agal bloom can explain the twitching nor the long duration of mortality particularly during winter months.

The presence of a toxic substance could explain the twitching, but no source of sufficient amount of any toxic material could be identified, despite a range of relevant sediment and water measurements, and based on expert assessment of this and literature evidence. Although a range of chemicals, including pyridine, are known to be toxic to crustaceans, the wide geographical spread and long duration of the event would require sustained release of very large volumes of the chemical which is considered very unlikely from point sources or due to dredging as a cause for unusual crustacean death.

It is also possible that several of the stressors considered in this report operated together to degrade the marine environment and lead to the unusual mortality.

1 Introduction

On the 4 of October 2021 bait collectors reported dying crabs on shores of Bran Sands in the north-east of England. This was followed by more sightings of morbid or moribund crustaceans over the course of the following weeks along the north-east coast of England, extending from Spittal Beach in the north to Scarborough in the south. At the time of writing, there have been 3 periods with notable numbers of wash-ups of crustaceans (October to November 2021, April to June 2022, September to December 2022) with the first two episodes including incapacitated live crabs with unusual twitching behaviour.

Initial investigations by Defra Group, for the events of October to November 2021, could not definitively identify a cause, but concluded that algal blooms may be of significance. The local fishing community commissioned a study by leading Northeast Universities, led by Dr Caldwell of Newcastle University, to look further into probable causes. This group concluded that chemically toxic levels of pyridine, released by dredging in the area, was the most likely cause of the mortality event.

In October 2022, the Environment, Farming & Rural Affairs (EFRA) Select Committee heard evidence from various relevant groups and wrote to the Defra Secretary of State requesting that an independent review was commissioned into the causes of the unusual deaths. In response, the Defra Chief Scientific Adviser (CSA), Professor Gideon Henderson was asked to set up a panel of independent experts, with oversight from the Government CSA (GCSA) Professor Sir Patrick Vallance. The resulting panel - The Crustacean Mortality Expert Panel (CMEP) - was established with experts from academia and industry with a range of knowledge and experience spanning crustacean biology, marine eco-toxicology, sea-life histology/pathology, marine pollutants, algal blooms, chemical dispersion in the oceans, dredging and coastal processes, and sediment and water chemistry.

The CMEP was tasked with providing an independent scientific assessment of all the possible causes of the mass crustacean mortality incident using all the relevant available data, including the two prevailing theories of algal blooms and pyridine toxicity from dredging. The CMEP's remit did not extend to consideration of government processes during the investigation of the mortality event(s), food safety, nor the economic implications of the deaths.

The panel grouped their consideration into four sections:

- **Disease pathology**: That the deaths were caused by a disease or parasite.
- **Harmful algal bloom**: Including algal toxins released by the bloom, and oxygen depletion associated with the bloom.
- **Chemical toxicity**: From chemicals (including pyridine) released by industry at the shore or by unusual run-off from the shore.

- **Dredging**: The specific release of a toxic chemical (including pyridine) as a result of disturbance and resuspension by dredging or disposal of the dredged sediment.

The structure of this report reflects this division. The panel also considered the combination effects of multiple stressors.

As part of the panel's inquiries, they sought and considered data from diverse sources, including from the Environment Agency (EA), Marine Management Organisation (MMO), Centre for Environment, Fisheries and Aquaculture Science (Cefas), the Newcastle University led research group, the Port Authority and Defra. All data considered is cited or listed in the accompanying document.

This report represents the consensus views of the CMEP.

2 Timing, locations, and nature of deaths

Observations of the locations and dates of crustacean deaths were compiled by the Environment Agency, along with other relevant associated observations. These are summarised in Figures 1 to 5. This compilation of data on mortality observations is used in consideration of the likelihood of all possible causes of mortality.

Key aspects of the data on mortality are: the broad geographical extent (at least 70 km); the initial duration of deaths from early October to early December 2021 and subsequent periods of mortality in 2022; the twitching observed in dead crabs along much of the coastline; and the dominance of crustacea relative to other species.

Fig 1: Location map for the coastline from which unusual crab wash ups were reported between October and November 2021, adapted from the Environment Agency's incident investigation summary. Locations with washups shown in Figures 2 to 5. Key industrial facilities considered as possible point source pollution are marked with black dots, and the extent of dredging in the Tees and dredging disposal site are outlined in black. (22_1BH_NEIFCA wash up incidents and logs record October 2021 to September 2022; 23_1BH_Wash Up Reports September to December 2022).

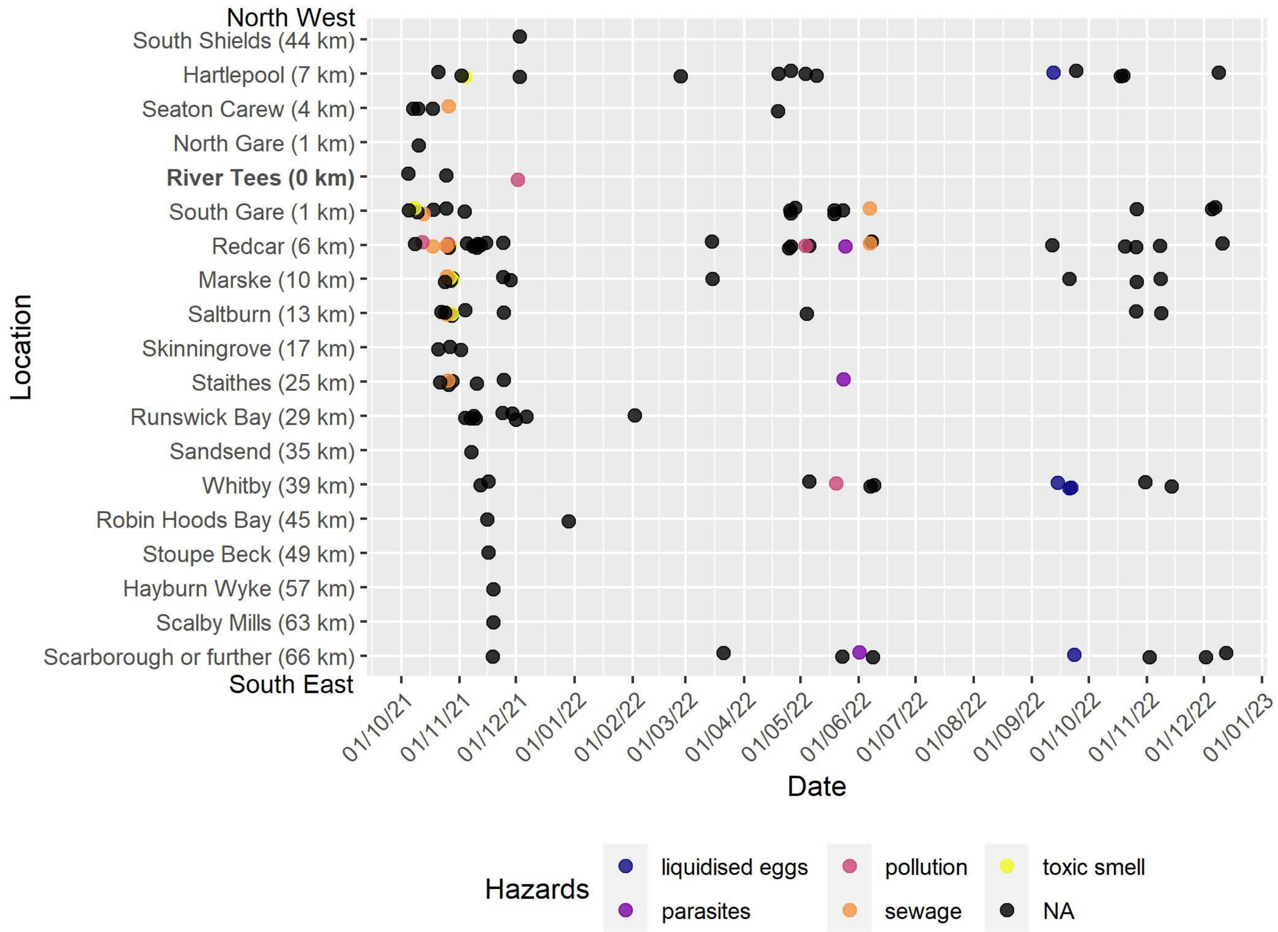

Fig 2: Observed locations of animal wash-ups between September 2021 and December 2022, colour coded by other information about possible hazards. Data from Hazards are the terms used by the public or officers who reported the incidence. The location distance is from the River Tees (in bold). (22_1BH_NEIFCA wash up incidents and logs record October 2021 to September 2022; 23_1BH_Wash Up Reports September to December 2022).

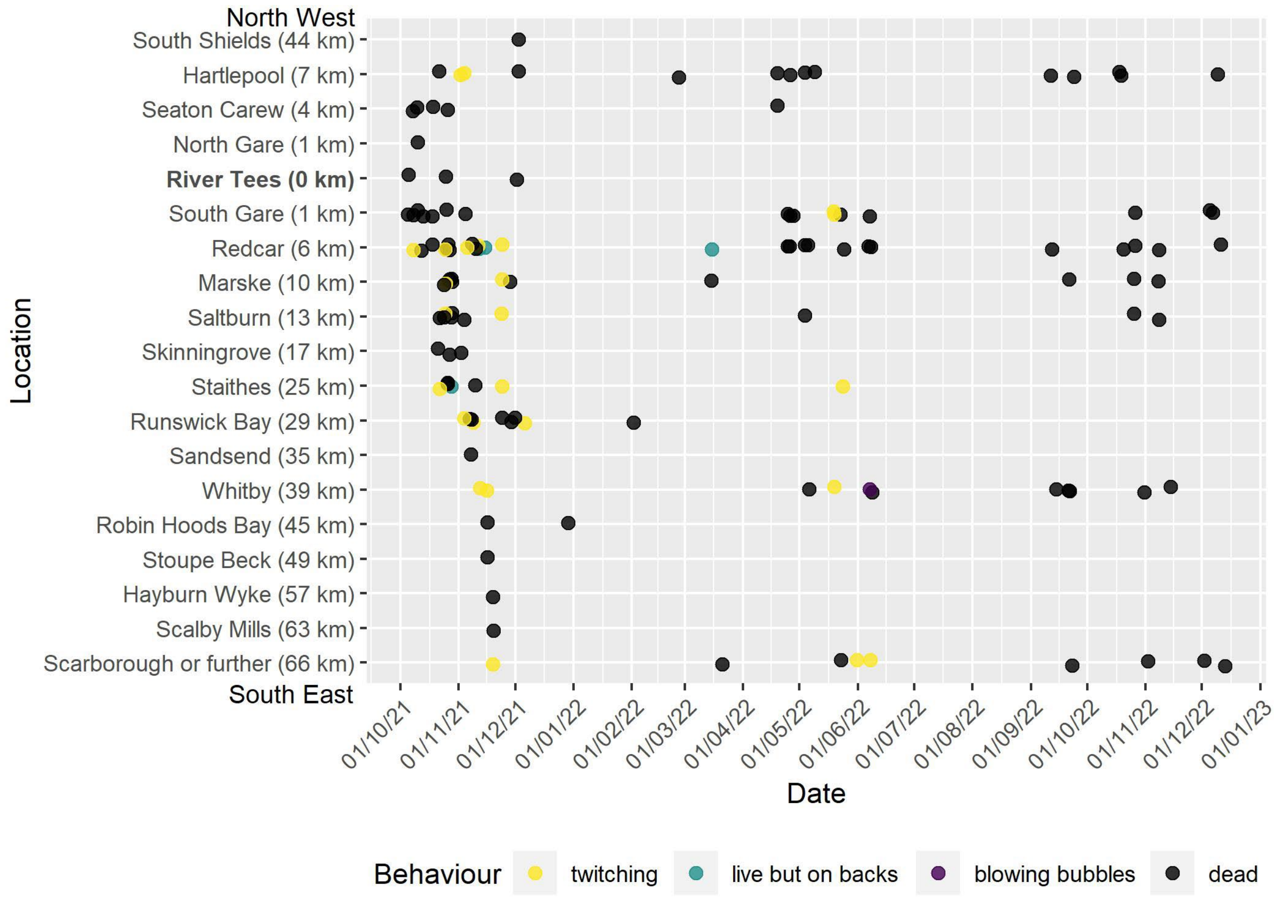

Fig 3: Observed locations of animal wash-ups between September 2021 and December 2022, colour coded by status of the animal, including (in yellow) crabs and lobsters exhibiting the unusual twitching behaviour. The location distance is from the River Tees (in bold). Data from (22_1BH_NEIFCA wash up incidents and logs record October 2021 to September 2022; 23_1BH_Wash Up Reports September to December 2022).

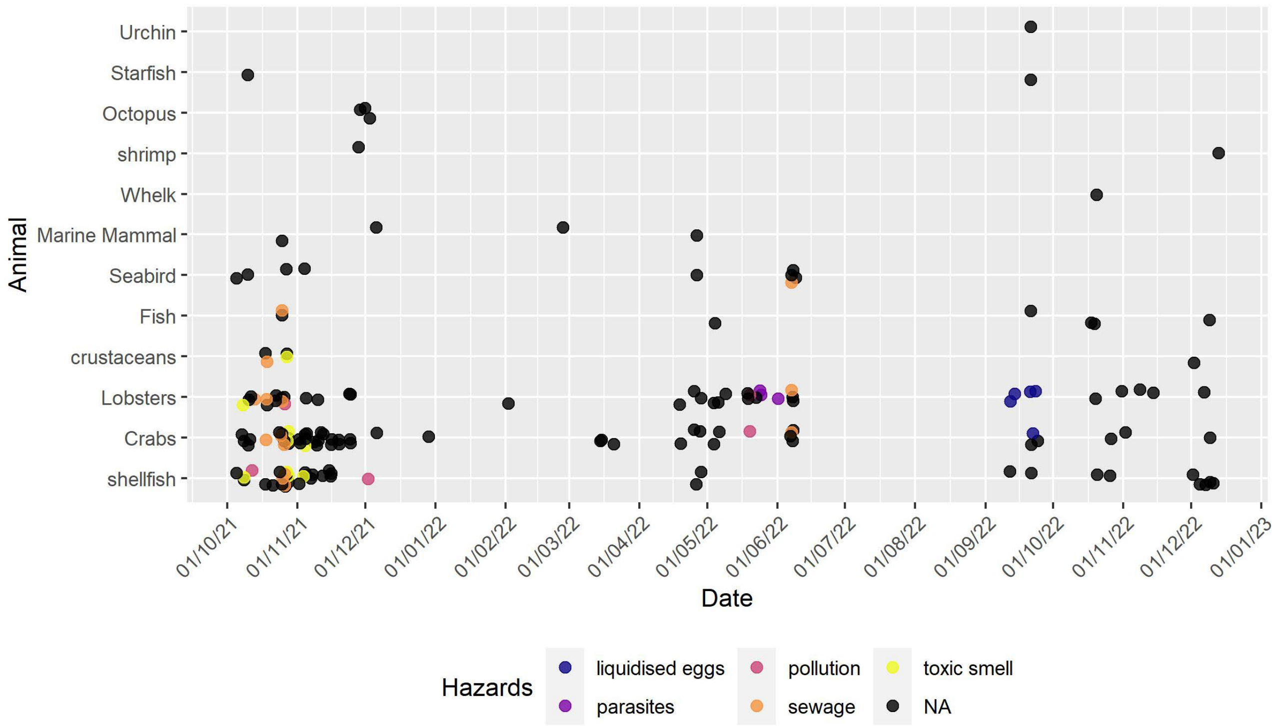

Fig 4: Species wash-ups between September 2021 and December 2022, colour coded by other information about possible hazards. Data from Animals are the terms used in reports from the public and officers, as a result crustaceans, crabs, lobsters, and shellfish should not be seen as distinctly separate categories. Hazards are the terms used by the public or officers who reported the incidence. (22_1BH_NEIFCA wash up incidents and logs record October 2021 to September 2022; 23_1BH_Wash Up Reports September to December 2022).

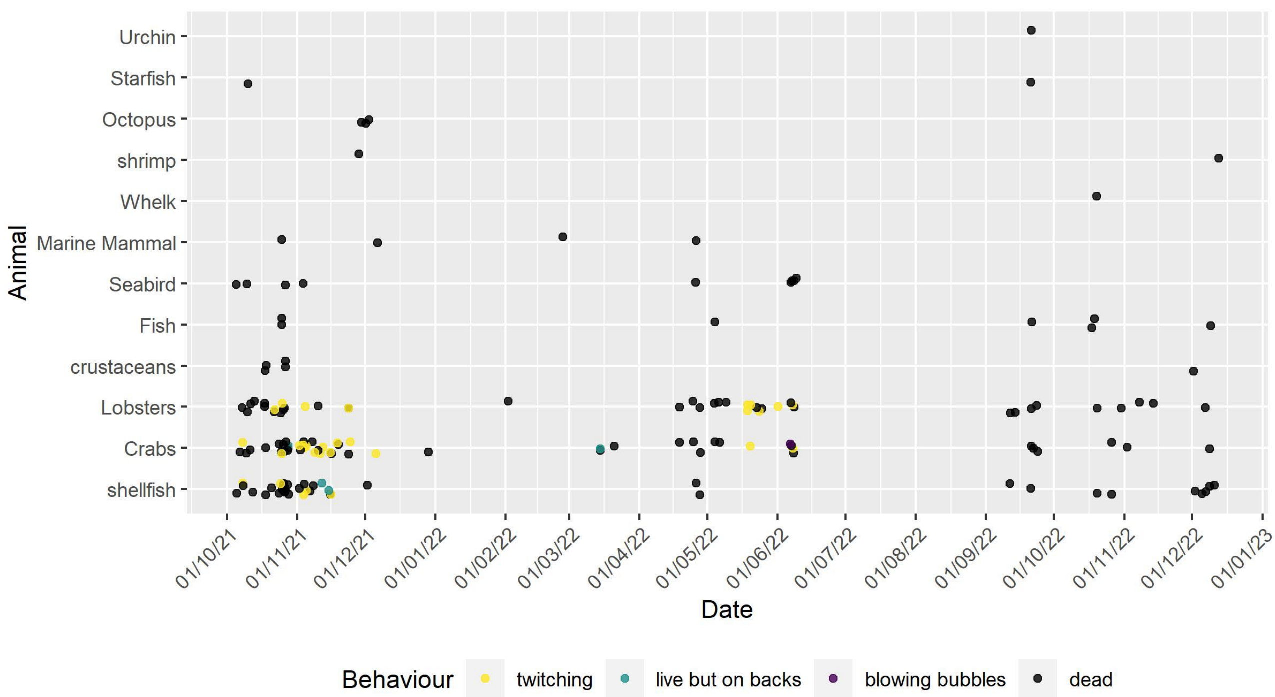

Fig 5: Species wash-ups between September 2021 and December 2022, colour coded by status of the animal, including (in yellow) crabs and lobsters exhibiting the unusual

twitching behaviour. Animals are the terms used in reports from the public and officers, as a result crustaceans, crabs, lobsters, and shellfish should not be seen as distinctly separate categories. (22_1BH_NEIFCA wash up incidents and logs record October 2021 to September 2022; 23_1BH_Wash Up Reports September to December 2022).

3 Disease Pathology

Consideration was given to the following questions:

1. can a disease cause mass mortality of crustaceans at a regional scale?
2. what was the approach taken by Cefas to look at disease as a causative agent?
3. what was the pathology of the crabs observed off Teesside, and how does this relate to the possible causes?
4. what is meant by 'twitching' among the impacted crabs?
5. what symptoms would the potential causal factors exhibit in decapod crustaceans?

3.1 Can disease cause mass mortality on crustaceans on a regional scale?

There is considerable evidence in the literature that large scale die-offs of crabs and lobsters have been attributed to disease (Messick and Sindermann, 1992; Mullen et al., 2004; Stentiford and Shields, 2005; Wang, 2011). For example, Mullen et al. (2004) reported that an estimated 11 million lobsters died off the coast of Long Island Sound (USA) in 1999. Initially their investigations looked into dredging, chemical contaminants, and disease. No significant amounts of trace elements, polycyclic aromatic hydrocarbons, polychlorinated biphenyl congeners, or pesticides were observed in lobster tissues and the study failed to isolate any bacteria from the hemolymph and hepatopancreas (Mullen et al., 2004). What the study did observe was considerable infection from a protozoan parasite throughout the nervous tissues of impacted lobsters, leading the authors to conclude that this parasite was the primary cause of mass mortality in 1999. These have been known to cause mortality events in other sea life including crabs and sea urchins (Newman and Ward, 1973; Jones and Scheibling, 1985; Bower et al., 1994; Bateman et al, 2022).

Edible crabs and lobsters have been in decline along the south-east coast of England for the past 5 years (Sussex IFCA, 2021). The Manhood Peninsula Partnership, a regional collaborative, has initiated a project on *Crustaceans, Habitat and Sediment Movement* (Link to CHASM). One particular line of inquiry for the CHASM project has been sedimentation following dredging in the local area, in particular capital dredging of 3 million m^3 around Portsmouth Harbour in 2016 to allow access for new aircraft carriers. For example, Lobster landings have shown an annual decline (41 tonnes in 2017, 32 tonnes in 2018, 19 tonnes in 2019, 11 tonnes in 2020 to 8 tonnes in 2021) and edible crab landings have shown a similar trend (179 tonnes in 2018, 158 tonnes in 2019, 66 tonnes in 2020 to 48 tonnes in 2021).

However, summary reports from several inshore fisheries and conservation authority (IFCA) regions (Devon, Cornwall, Southern, Northumberland) have seen declines in edible crab landings since 2017, even without the presence of dredging, indicating something more widespread might be occurring. Following the declines off the Sussex coast, Cefas investigated disease as a possible causal factor. The results, published in Bateman et al. (2022), report the finding of an amoebic crustacean disease (ACD) in edible crabs (*Cancer pagurus*) for the first time in UK waters, which belong to a similar group of parasites reported to have caused the lobster mortalities in the USA (Mullen et al., 2004). They go onto report “Data from previous edible crab health surveys conducted at Cefas between 2002 and 2021 (Stentiford et al., 2002, 2003, 2007, Bateman & Stentiford 2008, Feist et al., 2009, Bateman et al., 2011, 2016, Hartikainen et al., 2014) were re-evaluated to determine whether pathologies like those described here were present. A total of 620 edible crabs sampled directly from fisheries in the English Channel and 2860 juvenile edible crabs collected from the shoreline at 4 separate sites around the coast of England and Wales were examined over this period. None of these samples reported histological evidence of a paramoebid infection or associated pathologies consistent with paramoebiasis within the tissues”. Bateman et al. (2022) were able to conclude that the more recent finding of an ACD represents a novel parasite to the UK and suggest that further studies are required to investigate the potential role of ACD as a mortality driver in commercially exploited populations of *C. pagurus* in European waters. In a follow up email in response to a question from CMEP (20 December 2022) Cefas highlighted “that this emerging disease was unlikely to be responsible for the declines in the south coast crabs and it was not observed in the samples obtained in the north-east of England” (CEFAS, pers. comm., 20 December 2022).

CMEP considered the possibility of an unidentified novel crustacean disease in the UK. They found research reporting on a number of viral and parasitic diseases that may not have been screened for by Cefas in the crab and lobster samples, for example viruses (Bateman and Stentiford, 2017; Zhao et al., 2021). These diseases include reoviruses which are known to infect a broad range of crustaceans (see review by Bateman and Stentiford, 2017) and which have sometimes been reported as causing similar symptoms to the crustaceans impacted by this event. For example, Johnson & Bodammer (1975) found that a Reo- like virus was responsible for mortality among Blue crab populations with a pathology associated with tremors and mortality within 3 days, at Chincoteague Bay, Virginia, USA. Zhao et al., 2021 report that the typical signs caused by reovirus infections in brachyuran crustaceans are “lethargy, anorexia, trembling and paralysis at late phases of the infection”. In their review they go on to outline that experimental infection can result in rapid and high mortality (Zhao et al., 2021). Wang and Gu (2002) reported that Chinese mitten crabs infected with a Rickettsia-like organism were “typically lethargic with loss of appetite and paroxysmal tremors of the pereiopod, hence the term ‘tremor disease’ given by the local fishermen. Infected crabs exhibited signs of weakness, anorexia, paroxysmal intense tremors and death in succession”. Therefore, the pathology of crabs associated with disease can be similar to the ‘twitching’ observed in the north-east of England. Knowledge of these viruses in UK crustacean populations is currently limited and hampered by limited molecular information on crabs (Bateman and Stentiford, 2017). Furthermore, many viruses are not found in isolation and act synergistically (Bateman and Stentiford, 2017).

It is possible that there is a novel disease agent in the UK, similar to those thought to have caused the 'uncontrolled convulsive twitching' seen in the north-east mortality event. To further assess this possibility more information was sought from Cefas about the methods used in their disease screening and to specifically ask Cefas if they could be confident in ruling out novel disease agents to the UK through their standard histopathology disease screens. This is discussed in Section 3.2. Cefas confirmed that some pathogens would have been harder to see when samples were not screened from fresh or well preserved specimens. Therefore, Cefas highlighted that "it is possible there could be a novel pathogen not identified as yet and it is not likely that we can definitively eliminate the involvement of a potential novel pathogen".

Summary: There is a possibility of a novel pathogen causing declines in crustaceans in UK waters.

3.2 What was the approach taken by Cefas

Cefas undertook histological and molecular analysis of a number of crab and lobster samples following the mass mortality event which included: Between 19 October and 24 November 2021 a total of 33 edible crab (*Cancer pagurus*), 11 native lobster (*Homarus gammarus*), and 5 shore crab (*Carcinus maenas*), a couple of Velvet swimming crabs (*Necora puber*; number unconfirmed), were also assessed for disease agents.

Note that, when Cefas reports on molecular screening of known listed diseases, this refers only to White Spot Syndrome Virus (WSSV), because this is the only listed native crustacean disease they are statutorily obliged to screen (link to legislation). Further analysis was conducted histologically.

Table 2: Summary of Histological and molecular analysis of crab and lobster samples between 19 October and 24 November 2021

Date	Species (number, location and presentation)	Test	Results
19 October 2021	• Brown crab (7, Redcar) • Native lobsters (2, Bran Sands) • Shore crabs (5, Bran Sandsand Seaton)	Molecular screening WSSV	Negative

Date	Species (number, location and presentation)	Test	Results
21 October 2021	Brown crabs (16, merchant in Hartlepool)	Screened for known listed disease (WSSV) by molecular PCR techniques, and full disease screen for bacteria and histological analysis (all internal organs screened for disease including heart, gill, hepatopancreas, muscle, gonad, new shell).	Negative for WSSV, some bacteria present (Vibrio spp. and *Marimonas aquiplantarum*) but no pathology was observed in association with the bacteria. Histopathology reported no disease agent.
11 November 2021	Lobsters (9) and edible crabs (8) (3 miles east of Redcar. Two of the lobsters were displaying lethargy/non-righting behaviour and twitching)	PCR for WSSV, histopathology	All samples negative for WSSV. The 2 lobsters showing clinical symptoms were negative for any disease agent through histopathology. Presence of *Hematodinium* in 1 brown crab and 3 others infected with *Paramikrocytos canceri*. This pathogen is not considered consistent with the mortality event, nor was the pathogen detected in lobster (which were displaying clinical signs)
24 November 2021	• Crabs (6, shore, edible and velvets; Runswick Bay; found moribund). • Edible crab (2, caught off Whitby (within 3 nautical miles); lethargic and dying)	PCR for WSSV Histopathology	All samples negative for WSSV, Low levels of Hematodinium sp. and Digenean, 1 brown crab showed low levels of Paramikrocytos canceri in the antennal gland

Cefas concluded that there was no evidence from the samples that there was an infectious disease agent responsible for the mortalities observed and they therefore did not believe that an aquatic animal disease was the likely cause of this event (from Ref: EW033-I-756 PM 41921, 41844, 42035, 42123).

In response to a query from CMEP (email 22 December 16:47) on the extent of the molecular screens Cefas wrote “The initial disease screens covered only a small number of diseases. We have looked at histology for the amoebic disease but this only works well on freshly killed animals as the tissue degraded quickly after death”.
It appears that samples they received were degraded making detection of some pathogens difficult histologically. It would therefore be useful for archived samples to be retrospectively screened for a broader range of potential pathogens, and to collect appropriate samples in the future to be able to screen for all potential pathogens.

3.3 What was the pathology of the crabs observed off Teesside, and how does this relate to the possible causes?

Initial site reports from the Environment Agency (8 October 2021) highlight that officers reported 100s of crabs which were dead or in the process of dying and that they were “exhibiting a strange lethargic twitching behavior – either on their backs or on their fronts but not able to move in any controlled manner”. They go on to report that “this was true of crabs both submerged under the water and exposed/washed up at low tide. Dead lobsters washed up were also observed”. There was no other signs of pollution (smell, change in water colour or debris). All other marine organisms were seen still alive including mussels, lug worms, tube worms, periwinkles, barnacles and fish, it only seemed to be Crustacea affected.” (11_1BH_Crab investigation 8.10.2021.pdf). The EA incident investigation summary highlights that “only crabs (green shore, velvet swimming, edible, porcelain), and lobsters were observed as impacted (range of ages classes). On both shore visits crabs were either dead, or on their backs twitching/ very lethargic with no fight left in them.” (02_7EA_EA_Incident_Investigation_summary_Oct_Dec.doc).

These observations are supported by videos which the panel has seen and verify claims of crabs twitching on their backs. The EA Stakeholder briefing document states: “Reports of other animals, including octopus, limpets and shrimp found dead in the area appear to be unconnected and are more likely to be a result of storms and bad weather in the area.” (03_7EA_Crab_deaths_Feb_stakeholder_update_final.doc). Furthermore, an Aquatic Environments consultancy report to the EA highlights “Having visited the six shores on the north-east coast of England in quick succession on the 20 and 21 January 2022, following the mortality event that occurred in the autumn of 2021, it appears that there has been a significant impact on the ‘true crab’ intertidal populations. No shore crabs or swimming crabs were recorded within the known zone of the event, whilst healthy populations were seen outside the area. Shore hermit crabs and possibly squat lobsters appear to have been less affected by the event, as their populations appear to be recovering and they were found (sometimes in good numbers) on the shores in the south of the area. From the limited observations made on these single post-event visits, it appears that the rest of the ‘rocky shore’ ecosystem has survived intact” (01_1BH_Aquatic Environments decapod mortality results.pdf).

3.3.1 What is meant by ‘twitching’ among the impacted crabs?

The CMEP considered the ‘twitching’ reported among the washed up crabs as critical to ruling in or out various causal factors. Videos of this behavior show a variety of crabs in various habitats, including offshore trawl collected and shore collected specimens. The majority of the videos show moribund crabs either in low water or in buckets having been trawled, and it was difficult to assess the specimens. However, there were a few videos which stood out to the panel as providing good examples of what is likely meant by the observers using the term ‘twitching’. We refer to this hereafter as ‘uncontrolled convulsive twitching’ It should be noted that in some published literature this response is referred to as “paroxysmal intense tremors” (Wang and Gu, 2002). This behaviour is best indicated by the video log: GAWV0487.MP4 (Folder 03_21_1_BH_8th Oct 21). This shows a swimming crab in a small rockpool exhibiting ‘uncontrolled convulsive twitching’, with its legs moving in an uncontrolled manner, not seen in healthy specimens (see also IORV0148 – as above). Similar examples can also be seen in the ‘Vessel Surveys’ folder (07_22_1BH_Trawl videos 14_18.11.21; IMG_3230; IMG_3231 and 3232) showing the harbour swimming crab (*Liocarcinus depurator*) exhibiting uncontrolled convulsive twitching of swimming limbs. These should be compared with normal swimming crab behaviour, seen at the control site at Robin Hoods Bay (video IMG_3183).

Further videos of uncontrolled convulsive twitching can be seen in the following folder: 05_22_1BH_Trawl images 18_19.01.22 (Off Seaton Carew All Crabs Video; 5. Skinningrove Wick *L. holsatus* Video 2 (also 1 x *C. cassivelaunus*); 7. Sea Off Saltburn All Crabs Video 1).

Some of the other videos could be construed as ‘normal’ moribund/dying behavior. This can be seen in some videos of crabs lying on their backs exhibiting very little movement apart from the occasional twitch of a leg (for example video IMG_1476 in Folder 03_21_1_BH_8th October 21). The panel thought that these were inconclusive as there was no way to determine how long the crabs had been impacted, and could represent specimens that had previously been more actively ‘twitching’, but were now more advanced in pathology.

In summary: There were definite signs of uncontrolled convulsive twitching in some of the video evidence. This presents differently to normal moribund or dying behaviour of crabs.

3.4 What symptoms would the potential causal factors exhibit in decapod crustaceans?

3.4.1 Disease various - amoebic crab disease (ACD) specifically

Crabs and lobsters were observed moribund, limp and twitching which has been associated with some diseases (Newman and Ward, 1973; Jones and Scheibling, 1985;

Bower et al., 1994; Mullen et al., 2004; Bateman et al., 2022). For example, Mullen et al., 2004 reported lobsters were “limp” which was interpreted clinically as paretic and flaccidly paralysed. Crabs/lobsters observed off Selsey were observed to be moribund and dead within pots (Bateman et al., 2022), but not twitching; however Cefas felt that the clinical similarities between those in the north-east of England were worth investigating for ACD. Cefas did not find any signs of the *J. feistie* (ACD) parasite, and felt that this emerging parasite had not caused the mass mortalities in the south to their knowledge, even though the clinical picture was similar. Twitching or tremors have been reported to be a symptom of several pathogens worldwide including reo or reo-like viruses, spiroplasma bacteria and amoebic crustacean disease (Johnson and Bodammer, 1975; Zhang et al., 2004; Wang, 2011; Zhang and Bonami, 2012).

The CMEP considered that the symptoms described in the north-east of England, including autotomy and twitching (referred to as tremors in some literature), are consistent with a variety of diseases in crustaceans.

3.4.2 Toxic pollutants various

The ‘uncontrolled convulsive twitching’ and autotomy evident from video footage (see Section 3.3) of the stranded crustaceans seem similar to the neurotoxic effects of some pesticide exposures. These are referred to in the ecotoxicology literature as ‘spasms’ or ‘spasming’. Schroeder-Spain et al., (2018) reported that blue crabs (*Callinectes sapidus*) exposed to two pesticides (Malathion and Carbaryl) had “Muscle spasms and uncontrolled limb movements in both pesticide treatments” resulting in an inability to right themselves and mortality at higher concentrations. Similar behavioural observations have been observed for blue crab exposed to pyrethroid pesticides (resmethrin; Schroeder-Spain and Smee, 2019) and neotropical crabs (*Poppiana dentata*) exposed to organophosphate insecticides (Singh et al., 2022). Twitching can also be induced by exposure to naturally occurring toxins in the mucus of nemertean-worms. Injection of mucus-derived peptides from the worm Lineus longissimus into *Carcinus maenas* results in rapid onset of involuntary tremors of the limbs, followed by hypertonus and paralysis via their action on voltage-gated sodium channels in the crab nervous system (Jacobssen et al., 2018). It is not suggested that nemertean toxins are the cause of the mass mortality in the north-east of England, but we draw on this published description of the neurotoxic effects of a marine toxin as a comparison to the ‘uncontrolled convulsive twitching’ pathology which was observed during the event. Further studies have demonstrated that injection from a wide variety of compounds such as monoamine neurotransmitters can induce tremors/twitching (Huddart and Batram 1984; Wood et al.,1995; Quesada et al., 2011).

3.4.3 Algal bloom toxins

Naturally occurring algal toxins from harmful algal blooms (HABs) were measured and detailed in the reports (Testing of crustacean tissue samples report, June 2022). To the panel’s knowledge these agents have not been shown to induce the observed pathologies in invertebrates.

A number of studies have indicated that crustaceans are immune to Paralytic and Diarrhetic Shellfish Poisoning toxins (PSPs and DSPs). For example, larvae of the American lobster (*Homarus americanus*) appear immune to PSP toxins (gonyautoxin II, -III and -IV, neosaxitoxin and saxitoxin) (Robineau et al., 1991), whilst adult lobsters fed with PSP toxins from the dinoflagellate *Gonyaulax tamarensis* (now *Alexandrium catenella*) were unaffected (Yentsch and Balch, 1975). Dungeness crabs (*Cancer magister*) can accumulate high levels of domoic acid (2.85 mg) over several weeks with no ill-effects reported (Lund et al., 1997).

Lipophilic toxins, Azaspiracids, were elevated in some of the samples taken (up to 50 μg/kg AZA1, Table 3, Testing of crustacean tissue samples report, June 2022), but have also been reported in *Cancer pagurus* tissues at 733 μg/kg in Norway (Torgersen et al., 2008). No adverse effects to the crabs were reported in this Norwegian study. Okadaic acid (DSP) has also been found in *Cancer pagurus* tissues in Norway at 290 μg/kg (Torgersen et al., 2005).

None of the above studies mentions recorded pathology or mortality in the crustacean species investigated. Therefore, given that the concentrations of HAB toxins in the crustacean samples were not high, and that crustaceans are known to accumulate such toxins to much higher concentrations without the observed pathology, the panel thought HAB toxins as unlikely as a causal factor.

3.4.4 Hypoxia

Under hypoxic conditions we would expect crustaceans to exhibit avoidance behaviour (Haselmair et al., 2010; Diaz & Rosenberg, 1995), eventually becoming more lethargic and moribund (if escape is not possible) as the health declines prior to death (Haselmair et al., 2010; Diaz & Rosenberg, 1995). Despite searching for reference to this behaviour specifically, the panel did not find any published evidence for ‘uncontrolled convulsive twitching’ in decapod crustaceans under hypoxic conditions. Uncontrolled convulsive twitching is not expected under hypoxic conditions.

3.4.5 Conclusions

The twitching observed is consistent with a variety of diseases in crustaceans, or with a toxic agent. Algal bloom toxins and hypoxia are unlikely causative agents for the twitching observed.

3.5 Does the fact that only crustaceans were impacted point to a causal factor?

This event only appeared to have effects on larger decapod crustaceans (including edible crabs, lobsters, common shore crabs and velvet swimming crabs, but not hermit crabs) (see Section 3.2: reports including:
02_7EA_EA_Incident_Investigation_summary_Oct_Dec.doc;
03_7EA_Crab_deaths_Feb_stakeholder_update_final.doc; 11_1BH_Crab investigation 8.10.2021.pdf).

The panel, however, thought it was noteworthy that relatively large numbers of curled octopus (*Eledone cirrosa*) were observed washed up dead on the shore at similar locations, and approximately 1 month after the crabs. It was reported to IFCA on the 29th November 2021 by a number of the public that 100's of octopus were washed up dead on Runswick Bay. An IFCA officer attended on the 1st December 2021 and spoke to dog walkers who also reported 100's of dead octopus. The officer could not confirm if the numbers were in the hundreds, due to the rising tide cutting off parts of the beach, but did mention there were lots. On the 1 December a Facebook post, which included photos, reported a dozen dead octopus were washed up on Blast Beach and Hawthorn Beach (Seaham). In addition, on the 3 December 2021 IFCA officers received email reports of 30 to 40 dead octopus washed up on Hartlepool headland by a member of the public with some photo evidence. Also on the 3 December NE-IFCA logs an observation from Facebook that Littlehaven Beach (South Shields) "was littered with dead octopus". CMEP felt that finding one or two washed up dead octopus might not be considered too unusual but 100's, if correct, is unusual. The Environment Agency (EA) considered a number of theories to why this may have occurred from a natural die-off combined with a storm (as their lifespan is 2 years) and IFCA mentioned that Runswick Bay is the main habitat for octopus, to consideration of starvation given their main diet (crabs) had died. The counter argument is that food could well have been plentiful as it was dead and littering the seabed. It is also possible that octopus may have died from eating contaminated crabs, or died of the same things as the crabs.

The CMEP also identified one study into high octopus mortality following storm discharges in Portugal which were attributed to urban runoff and found high levels of lead within tissues (Raimundo et al., 2017).

The CMEP supports the EA conclusion that deaths of other species reported anecdotally (for example razor clams, seals, birds) are more likely to be natural storm wash ups or other naturally expected events. However, the large mortalities of a major food resource might have a knock-on effect through the food chain, so some deaths could be attributed as a secondary effect.

3.6 Conclusions from pathological evidence, based on the available evidence

Based on the knowledge that a variety of crustacean diseases can induce a pathology similar to that observed off the north-east coast of England (particularly the uncontrolled convulsive twitching), and without further disease screening, **the panel concluded that disease was *about as likely as not* (33 to 66% probability) to be the cause of the mass mortalities reported in the north-east of England**. The panel agreed that this would move to either *very unlikely* (<10% probability) if results of molecular screening were confirmed as negative; or *very likely* (>10% probability) if a broad diagnostic screen of these potential pathogens proved positive.

Based on the available evidence, the CMEP came to the conclusion that the pathology seen in the dying organisms ('uncontrolled convulsive twitching') would also be consistent with a natural or anthropogenic stressor of the neural system. It was thought that this would be a *likely* cause of the observed pathology in the north-east of England if a source of such a neural stressor, for example, toxins, was present at sufficient levels.

4 Harmful Algal Blooms

4.1 Background

The marine phytoplankton community of coastal waters contain a relatively small number of genera and species that can under certain conditions cause harm to humans, our use of the marine ecosystem or other marine organisms. These harmful taxa are typically present at low background concentrations, but periodically increase in abundance to form harmful algal blooms (HABs). In UK waters most HABs are thought to occur naturally, promoted by a set of environmental conditions favourable to their development. However, anthropogenic factors can also promote blooms in certain circumstances.

A number of genera, principally the dinoflagellates *Alexandrium, Dinophysis* and the diatom *Pseudo-nitzschia* can produce a range of "shellfish toxins" that when accumulated within shellfish flesh make these shellfish harmful for human or other animal consumption. Most frequently toxicity events related to these species are associated with farmed shellfish (at which the bulk of monitoring is undertaken), but examples of wild crustacean mortality do exist (for example, Turner et al., 2018).

Mortalities of benthic organisms including crabs related to HABs have been reported in Ireland and the UK since the 1970s (Bresnan et al., 2021). The majority of these events have been related to the dinoflagellate *Karenia mikimotoi.* The ecology and harmful properties of *K. mikimotoi* have been reviewed by Brand et al. (2012) and Li et al. (2019). *Karenia mikimotoi* can reach very high densities in the water column and senescence of the bloom can result in it sinking to the bottom and killing benthic organisms through resulting anoxia from smothering or bacterial degradation of the organic material. The toxicity of *K. mikimotoi* is complex but the species is thought to produce haemolytic and cytotoxic, compounds and generates reactive oxygen species. There is evidence to suggest that both mechanisms may result in mortalities during blooms potentially depending on the hydrography of the location (O'Boyle et al., 2016). It should be noted that the temperature tolerance and toxicity of *K. mikimotoi* is different to that of brevetoxin producing *Karenia brevis* that is not found in UK or European waters, but typically in warmer waters such as the Gulf of Mexico. In both contexts (anoxia, toxin production) a wide variety of benthic biota are typically impacted by *K. mikimotoi* and mortalities recorded are comprised of multiple species groups ranging from lug worms, star fish, sea urchins, crabs, lobsters to fish and more. Mass mortalities relating to *K. miktmotoi* typically require significantly elevated cell densities in the range of hundreds of thousands or millions of cells per litre (cells L^{-1}) (see Table 1 of Li et al., 2009).

The panel considered the potential of the mortality event of 2021 in the context of a number of headings. These were:

1. What is the historic precedence for *Karenia mikimotoi* blooms and HAB related mortality events in region?

2. Was there an algal bloom in the waters along the north-east of England during September/October 2021?
3. Were the patterns of mortalities consistent with a HAB event?

4.2 What is the historic precedence for *Karenia mikimotoi* blooms and HAB related mortality events in region?

4.2.1 *Karenia mikimotoi* and mortality events in UK and Irish waters

Historical incidents, in the UK and elsewhere are summarised by Li et al. (2019). There are a number of recent recorded incidents of *K. mikimotoi* blooms resulting in significant benthic mortalities in the waters surrounding the UK and Ireland. Silke et al. (2005) report of a large bloom of *Karenia mikimotoi* in Ireland in 2005. The bloom reached nears 4×10^6 cells L^{-1} and resulted in the mortality of a wide range of benthic species including crabs (*Carcinus maenus, Portunus* sp) as well as fish, star fish, lug worms and other benthic biota. This report noted that the only animals that seemed to be "hanging on" in the most impacted areas were the Common Hermit Crabs, *Pagurus bernhardus*, and the Organ-pipe Worm, *Serpula vermicularis.* The following year an extensive bloom of *K. mikimotoi* in Scottish waters resulted in benthic mortalities including annelids, molluscs and some species of fish (Davidson et al., 2009). Baptie and Swan (2017) report the mortality of "great variety" of organisms, including lugworms, urchins and crabs again from *a K. mikimotoi* bloom of approximately 3.5×10^7 cells L^{-1}. Data from the Marine Scotland Scottish Coastal Observatory (SCObs) shows that cell densities of *K. mikimotoi* can exceed values of 1×10^6 cells L^{-1} at water temperatures ranging from 11.84 to 14.56 ^oC.

Karenia mikimotoi monitoring is limited in the north-east of England, but data from the Scottish regulatory biotoxin producing phytoplankton monitoring programme indicates that abundance of *K. mikimotoi* in the month of September have exceeded 100,000 cells L^{-1} in eight years since 2006. Elevated cell densities are therefore not unusual in September and in one year (2006) these elevated cell densities continued into October. Weekly phytoplankton monitoring by the SCObs shows with the exception of one record (3,500 cells L^{-1}) reported values in November and December are very low (<600 cells L^{-1}).

4.2.2 HAB mortality events in the north-east of England

While *K. mikimotoi* has been recorded in the north-east of England, to date there have been no records of mortalities of marine benthic biota as a result of a high biomass or *Karenia mikimotoi* bloom in the region. However, records of mortality events of marine organisms related to HABs in the north-east of England while rare, do exist. Reports in the literature come from the mortality of seabirds, particularly Shags (*Phalacrocorax aristotelis*) during June 1968 associated with the consumption of mussels contaminated with Paralytic Shellfish Toxins (PSTs) by the dinoflagellate *Gonyaulax tamarensis* (now *Alexandrium catenella*), an atypical event also associated with human illness (Coulson et al, 1968, Joint et al., 1997). There are also reports of Diarrhetic Shellfish Toxins (DSTs) in the livers of dead seabirds from the late 1990s in the IOC-ICES-PICES Harmful Algal Event Database (HAEDAT) although it is unknown if these toxins were the cause of death of these birds.

4.2.3 Shellfish toxin producing species in north-east of England

Regulatory monitoring of shellfish biotoxins and associated harmful phytoplankton for the Retained EU Regulation 2017/625 occurs in England and Wales but at relatively low spatial and temporal frequency, overseen by the Food Standards Agency (FSA). The monitoring site in the north-east of England is at Holy Island. Data on *K. mikimotoi* cell concentration is not reported as part of that monitoring programme. No biotoxins were found above the limit of detection at this site during 2021.

4.3 Was there an algal bloom in the waters along the north-east of England during September to October 2021?

4.3.1 *Karenia mikimotoi* during September to October 2021

During 2021, high abundances >1 x 106 cells L^{-1} of *Karenia mikimotoi* were recorded in and offshore from Orkney throughout August and >500,000 cells L^{-1} in Shetland and Moray Firth during late September. Anstruther in Fife reported a cell density of 5,760 cells L^{-1} on 6 September. Three EA monitoring sites in the north-east of England (Bamburg Castle, Northumberland and Beadnell Bay, The Bush) reported abundances of 306,033 cells L^{-1} (3 September), 358,309 cells L^{-1} (3 September) and 272,271 cells L^{-1} (4 September) respectively. While these data demonstrate that elevated *K. mikimotoi* were densities occurred on the east coast of the UK a month prior to the mortality event there is no phytoplankton cell count data immediately before or during the first week in October. Phytoplankton monitoring did not extend into October in the region, but phytoplankton cell densities typically decrease through October reaching low background values in November and the winter months (as was evident in the Scottish biotoxin producing phytoplankton monitoring that did continue during that part of 2021). It is therefore unlikely that a *K. mikimotoi* event would be responsible for the observed mortalities in late October or subsequently.

4.3.2 High biomass algal blooms

Chlorophyll concentrations are an indication of elevated phytoplankton biomass. High biomass might be expected to cause harm through deoxygenation when the bloom dies and sinks to the benthos, no matter the phytoplankton species involved. During the first week in September 2021, the EA directly measured (following acetone extraction) chlorophyll concentrations at a number of sites ranging from Bamburg Castle (8.4 µg L^{-1}), Northumberland and Beadnell Bay (10.0 µg L^{-1}), The Bush (2.0 µg L^{-1}). Chlorophyll values >10 µg L^{-1} were also recorded at a number of sites earlier in the year between March and June 2021 but are not associated with this event.

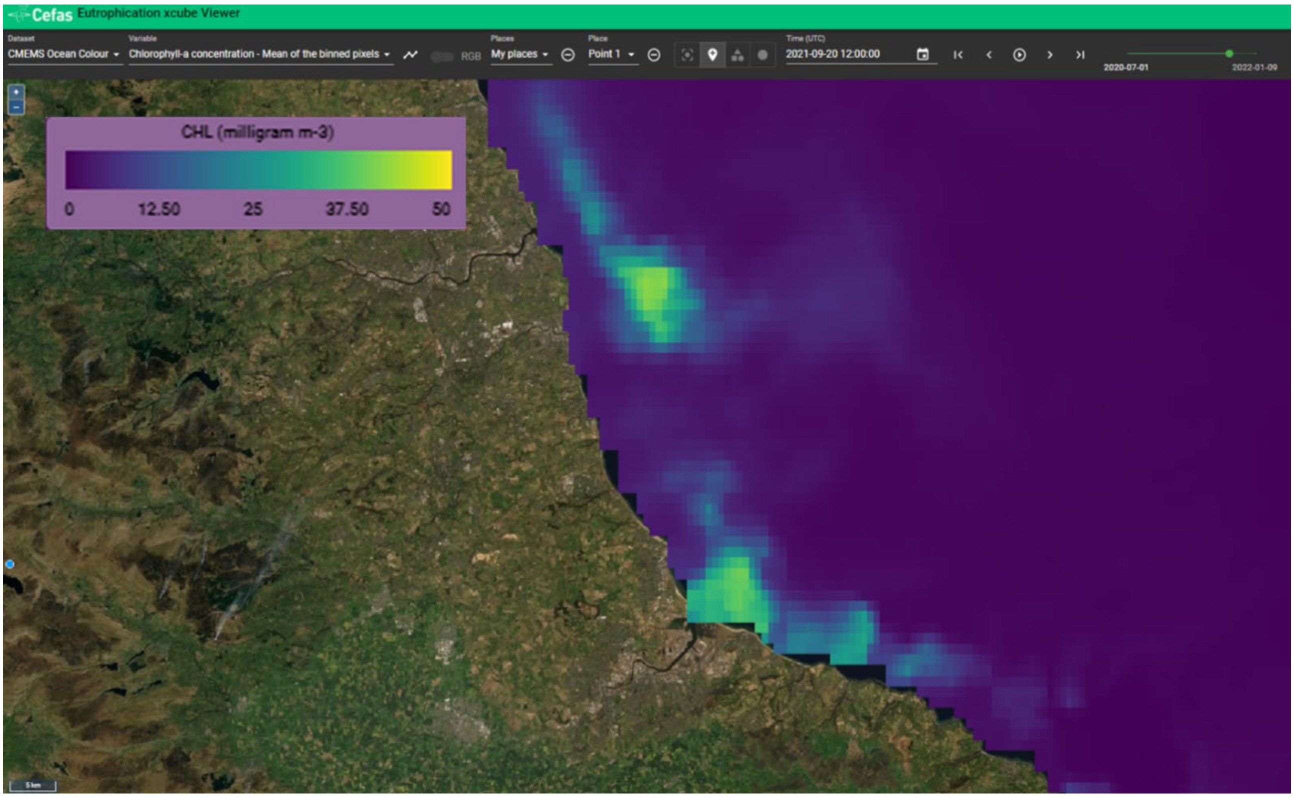

Fig 6: Satellite Image showing composite chlorophyll values during week 20 to 26 September 2021.

These measurements are consistent with satellite derived (EMEMS Ocean Colour) data that showed patches of very high chlorophyll concentration from the 20 to 26 September (>30 mg m^{-3}). These data (Figure 6) also demonstrate distinct offshore patches of chlorophyll (and hence algal blooms) that are very much dense enough to cause mortality should they relate to a *K. mikimotoi* (or potentially other phytoplankton) bloom that subsequently sank to the benthos. However, it must be noted that satellite derived chlorophyll estimates are less reliable in shallow, coastal waters such as these than offshore due to factors such as sediment resuspension. There is also no dissolved oxygen (DO) data from bottom waters in the region to support or counteract anoxia as a cause.

Plymouth Marine Laboratory applied a *Karenia* risk classifier to the area using satellite data from the NERC Earth Observation Date Acquisition and Analysis Service (NEODAAS) and processed following the methods outlined in Kurekin et al. (2014). This analysis identified the significant possibility that there was no bloom of *Karenia* present. High chlorophyll values detected could have been due to blooms of another phytoplankton species or suspended sediment. The limited phytoplankton monitoring prior to the mortalities being washed ashore mean there is insufficient information about the composition of the phytoplankton community during the period that high biomass was detected by satellite to ground truth the composition of this bloom.

4.3.3 Shellfish biotoxin blooms in the north-east of England

Data from the “Biotoxin and Phytoplankton official control monitoring programmes for England and Wales” operated by Cefas during 2021 (Coates et al., 2022) showed that Paralytic Shellfish Toxins, Lipophilic Shellfish Toxins (including Diarrhetic Shellfish Toxins) and Amnesic Shellfish Toxins were not detected above the limit of detection (LOD) in shellfish from the north-east of England. This monitoring programme employs “Trigger levels” of causative phytoplankton which are finite but relatively low abundances set to act as a potential early warning of harmful bloom development and possible subsequent toxin accumulation in shellfish. The associated causative organisms *Alexandrium* (PSTs), *Dinophysis* (DSTs) and Pseudo-*nitzschia* (ASTs) were not recorded above these “Trigger levels” during 2021. The benthic dinoflagellate *Prorocentrum lima*, a DST producer is the only species recorded above its “Trigger level” of 100 cells L^{-1}, but no DSTs above the LOD were recorded in shellfish at this site during the year.

4.4 Were the patterns of mortalities consistent with a HAB event?

4.4.1 *Karenia mikimotoi* or other high biomass bloom

Previous harmful *Karenia mikimotoi* and high biomass blooms have resulted in benthic mortalities that were broad and wide ranging (Silke et al., 2005, Davidson et al., 2009, Baptie and Swan 2017). The majority of reports are of mortalities in this event are of crabs and lobsters only. For example, a site visit to Bran Sands on 8 October by two EA officers reports 100s of dead crabs and many which were dying showing a lethargic twitching behaviour. Dead lobsters were also observed to be washed up. “All other marine organisms were seen still alive including mussels, lug worms, tube worms, periwinkles, barnacles and fish, it only seemed to be Crustacea affected”. Records of wash up and “twitching” behaviour observed in crabs and lobsters extend into mid/late November 2021. While the high algal biomass recorded by satellite at the end of September may have had an impact at the start of the event, given the storm in the area at the beginning of October 2021 and the expected die-off of phytoplankton at that time of year it is unlikely that an algal bloom caused an anoxia event that lasted for full duration of recorded mortalities.

These observations are a counter indicator to the event being related to an algal bloom either as (a) a *K. mikimotoi* bloom resulting in a toxic event or (b) *K. mikimotoi* or another high density algal bloom causing anoxia, as the negative effects of both of these bloom events are thought to be mostly indiscriminate rather than species specific (for example Silke et al., 2005). The weather and time of year suggest the sustained development of a high biomass algal bloom is unlikely.

We note that there is evidence that crustaceans are more susceptible to anoxic conditions than many other benthic organisms (Sunyer and Duarte 2008) [and see Section 4.4.2]. This might help to explain the selective mortality. However, while there is published evidence of harmful blooms impacting crab larvae (for example Gravinese et al., 2019), we are unaware of any previous records of selective adult crustacean mortality resulting from a harmful algal bloom.

4.4.2 Are decapod crustaceans (crabs and lobsters) more sensitive to hypoxia events?

A review of the published literature was undertaken to assess what is known about decapod sensitivities to hypoxia (Tables 3, 4 and associated references). A recent review article (Vaquer-Sunyer and Duarte, 2008), indicates that decapod crustaceans are more sensitive than many other benthic marine invertebrates to reduced oxygen environments. It has also been reported that susceptibility to hypoxia/anoxia is heightened in the presence of hydrogen sulphide (Haselmair et al., 2010), which is often elevated in anoxic aquatic conditions. Hydrogen sulphide levels were not measured in the current investigation.

Noteworthy were several reports of 'toxic/chemical' smells within the NE-IFCA logs (8 and 25 October 2021; South Gare, Saltburn, Marske) from IFCA and EA officers plus the public and fishing community whereby efforts were made to differentiate these from rotting smells of the dead/dying material. These observations of toxic smells also included several reports of sewage related smells both onshore and offshore from fishers and picked up from IFCA officers through photos of sanitary products on the shoreline.

It is important to note that the affected taxa are benthic organisms and therefore measurements of dissolved oxygen (DO) at the seabed are critical to determining whether there was a deoxygenation event at the time. Sea surface or midwater oxygen levels will not necessarily be informative of what is occurring at the seabed.

The EA measured oxygen levels at the time of the event from surface water buoys were all high (95 to 100% DO; [Link to Tees incident water data]). However, this does not provide evidence that there was no reduction of oxygen at the seabed at the time of the event. The EA did record at depth during vessel surveys (EA Vessel survey 15 to 17 November 2021) and also recorded high O_2 readings (95% plus DO at approximately 10 m depth) although these were measured some time after the initial event.

As noted in Section 4.4.2 the onset of hypoxia in decapod crustaceans is unlikely to result in the 'uncontrolled convulsive twitching' as was seen in this event.

Table 3: Limits of hypoxia on decapod species relevant to the present case.

Species	O_2 (mgO_2/L)	Measure of hypoxia	Reference
Cancer pagurus (European edible crab)	3.65*	**Critical oxygen tension (PcO_2, 60 to 80 Torr at 10°C)	Bradford and Taylor, 1992
Liocarcinus depurator (Harbour swimming crab)	2.43*	**Critical oxygen tension (PcO_2, 15 to 45 Torr at 14°C)	Gale , 1986
Carcinus maenas (Common shore crab)	1.43	Sublethal threshold	Hill et al., 1991

Species	O_2 (mgO_2/L)	Measure of hypoxia	Reference
Homarus gammarus (European Lobster)	0.7 to 1.33	Tolerated with no adverse effects	Rosenberg et al., 1991

*higher value taken from range. Animals tested were adult. **Oxygen units published as Torr were converted to mgO_2/L, [Link to online tool.]

Table 4: Limits of hypoxia on other decapod species.

Species	O_2 (mgO_2/L)	Measure of hypoxia	Reference
Homarus americanus (American lobster) (Juv.)	1.0	Lethal concentration LC_{50}	Miller et al., 2002
Cancer irroratus (Atlantic rock crab) (PL)	2.6	LC_{50}	Miller et al., 2002
Dyspanopeus sayi (Mud crab) (PL)	1.9	LC_{50}	Miller et al., 2002
Portunus trituberculatus (Marine crab) (Juv.)	2.9	Lethal	Li et al., 2017

Juv. = juvenile; PL = post larvae

Based on the available evidence the panel agreed that although decapod crustaceans are more sensitive than some other taxa to hypoxia, without evidence of hypoxia in the environment at the time of the event, this mass mortality could not be ascribed to it. In addition, the group have already considered that the symptoms seen, particularly the unusual twitching, were not concomitant with hypoxia related death/morbidity (see Section 4.4.2).

4.4.3 Other harmful algal taxa and toxins

Reports of the incident indicated that "Dying crabs and lobsters displayed characteristic 'twitching' and lethargic behaviour". It is unclear how widespread this behaviour was, but we are unaware of any such 'twitching' behaviour being recorded during previous *K. mikimotoi* mediated mortality events.

In terms of algal biotoxins, neurotoxins such as saxitoxin (PST) from *Alexandrium* or domoic acid (AST) from *Pseudo-nitzchia* may cause such behaviour given their potential to impact nerve transmission. There are many recorded cases of neurotoxins in crabs and other benthic organisms and Turner et al. (2018) proposed this as a cause of canine mortalities on English beaches in 2018. However, analysis of dead organisms from the 2021 incident identified only low levels of such neurotoxins in ~25% of animals, nor can we find any reports in the scientific literature of these toxins actually generating twitching in crustaceans. In addition, no ASTs or PSTs above the LOD were recorded in shellfish tested from the area during 2021 as part of the “Biotoxin and Phytoplankton official control monitoring programmes for England and Wales”.

As noted above some species of *Karenia* (but not *K. mikimotoi*) produce brevetoxins. These were not found in samples of dead crabs or lobsters. Other lipophilic toxins were present in finite concentrations (okadaic acid and Dinophysis toxin 2, azaspiracids, yessotoxins). Concentrations were generally low. Maximum measured concentration of diarrhetic shellfish toxins was 179 µg/kg which while above the maximum permitted limit for human shellfish consumption is not a particularly high concentration in comparison to others routinely measured in UK waters. These toxins are not known to cause acute mortality and hence it seems unlikely that they will have been the cause of this incident.

4.5 Summary

Historical evidence from the UK and Ireland confirms the potential for harmful algal blooms to cause acute mortalities of marine benthic organisms, including crustaceans. Recorded events are primarily related to the dinoflagellate *Karenia mikimotoi*.

There is evidence of an algal bloom in the region around the time of the initial crustacean mortality event in north-east of England but it is *unlikely* the bloom continued into late October of November, after the storm and as temperatures cooled further.

Direct measurements of algal biotoxins in crustaceans collected during the event show low levels of algal biotoxins and low abundance of causative taxa (*K. mikimotoi).* This suggests that algal toxins are *unlikely* (<33%) to be the cause of mortality.

Lack of *in situ* monitoring of oxygen levels during the event means that, while it a credible hypothesis that anoxia caused by a high biomass algal bloom could contribute to crustacean mortalities in late September and early October 2021, this is not fully testable.

Although HABs would normally cause mortality of a wider range of species, the susceptibility of crabs to lower oxygen levels means that particular mortality of crustaceans does not refute anoxia as a cause.

Observed pre-mortality twitching, and the continuation of crustacean deaths into November make it *unlikely* that anoxia cause by a HAB is the cause of the mortality.

5 Chemical Toxicity

5.1 Chemical pollutants as causative agents for mass mortality

Many activities that produce toxic chemicals, or that may lead to their escape into the environment, are regulated to limit possible environmental harm. Processes associated with this regulation, along with a range of measurements made by Government Agencies and by universities to investigate causes of mortality, provide a wide range of measurements of potential toxic agents.

Based on seawater and sediment measurements there is no evidence that labile metals, cyanide salts or other inorganic pollutants are the cause for the mortality events. Similarly, petroleum hydrocarbons (for example benzene, toluene, ethyl benzene, xylene (BTEX)) and industrial solvents were tested for but not observed or measured in seawater or sediments during the first period of mortality (September to December 2021).

The EA undertook mass spectral screening of affected and non-affected edible-crab tissue. This identified the presence of a very wide array of organic chemicals in crab tissues. Many of these can be considered as endogenous or naturally occurring chemicals. Others are of anthropogenic source, and include plasticizers (for example phthalates), tetrachloroethane (halogenated solvent) and low molecular weight, monoaromatic hydrocarbons (for example toluene, *m*/*p*-xylene and *p*-cresol). These pollutants were present in the crab samples collected from all the sites (meaning those with and without unusual mortality) and are common contaminants present in the coastal regions of the UK. Furthermore, low molecular weight hydrocarbons such as alkanes, alkenes, monoaromatics like toluene, xylene and the nitrogen-containing pyridine make up a large family of volatile organic compounds (VOCs) that are released as part of the post-mortem aging/decay process of biological tissues (Rosier et al., 2015) although the profile and quantity of these compounds in crustaceans during different stages of decay requires research.

Disposal of sediments dredged from UK coastlines to sea is a regulated process. Persistent organic pollutants like polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), organochlorine pesticides (OCPs) and polycyclic aromatic hydrocarbons (PAHs) are present in Teesside sediments along with heavy metals. Regulation requires, however, that before a sea disposal licence is granted, the concentrations of such contaminants in sediments proposed for dredging must be assessed according to the site-specific requirements of the MMO, advised by Cefas. As part of this process, sediment samples were collected throughout the estuary including from the shipping channel in the seaward entrance to the Tees Estuary (meaning Chart Areas 10, 11 and 12, see Annex D.1) in October 2021. Whereas the sample from Chart Area 12 showed relatively low levels of contamination, those from Areas 10 and particularly 11 were found to contain PCBs, PAHs and metals/metalloids at concentrations that are similar to those observed in the port area upstream in the Tees port area. These concentrations however are in the range typically observed in port regions impacted by a legacy of heavy industry (for example Annicchiarico et al., 2011) For example, concentrations of mercury and arsenic specifically in the channel sediments ranged from 0.05 to 0.76 mg/kg (dry weight) and 7.9 to 28.5 mg/kg. PAH concentrations displayed a wide range in the channel sediments, with concentrations of benzo[a]pyrene (B[a]P), a high molecular weight PAH, ranging from 0.02 to 1.41 mg/kg.

The current concentration thresholds for licensing the sea disposal of dredged sediments are based on Cefas's weight-of-evidence approach (review in progress, see Mason et al., 2022). Action Levels 1 and 2 for mercury are 0.3 and 3.0 mg/kg respectively and those for arsenic are 20 and 100 mg/kg. Currently ALs have not been set for individual PAHs but these chemicals fall under 'total hydrocarbon content', which, with an average concentration in the channel sediments of 208 mg/kg, exceed AL1 (100 mg/kg). PCBs concentrations fell below the AL1 threshold.

The disposal to sea of this dredged sediment will transport these largely particle–bound contaminants to the off-shore disposal ground. These chemicals are poorly metabolised and can accumulate in biological tissue, and hence are already present in the marine foodweb to varying degrees around the UK. However, extremely high concentrations in seawater (for example micro- to millimoles of PCBs and PAHs) would be required to achieve acute toxicity thresholds for an array of littoral-zone organisms (Sanchez-Bayo, 2006; Luís & Guilhermino, 2012; Donohoe et al., 2021) and such very high concentrations in the water column (particle-bound and dissolved) have not been observed in the affected region. As a result, it is *very unlikely* that the presence of persistent organic pollutants in the sediments is linked to the acute mass mortality events.

Overall, available measurements enable the panel to conclude that it is *very unlikely* that the unusual crustacean mortality was caused by any of the inorganic or persistent-organic pollutants that are measured for normal regulatory purposes.

5.2 Tributyl Tin

Di- and Tributyl Tin (for example TBT) is also reported in Teesside sediments via pre-dredging sampling and analysis submitted to the MMO. The use of TBT in antifouling paint on ships was banned in 2008 under the Convention on the Control of Harmful Anti-fouling Systems because of its toxicity to marine organisms (for example imposex in the Dog Whelk (*Nucella lapillus*)). TBT in sediment is therefore a legacy issue associated with shipping/boatyards. TBT concentrations in sediments collected in October 2021 (in the channel area described above) ranged from non-detect to 52 µg/kg. The current Cefas Action Levels are significantly higher than these measured values: 0.1 mg/kg dry weight (parts per million (ppm)) (Action Level 1) and 1.0 mg/kg dry weight (Action Level 2).

Wider picture on TBT: Cefas conducts an imposex survey approximately every 4 years and these have been conducted over 30 years following the discovery that TBT used in antifoulants are harmful to wildlife and cause the imposition of male characteristics (penis and vas deferens) in female gastropod Molluscs. The latest survey conducted by Cefas took place between March and April 2022. The species used in their surveys is the Dog Whelk which is a gastropod mollusc. The development of imposex in dog whelks takes approximately 6 months to manifest itself following exposure therefore any large-scale dredging or disturbance of sediments that may mobilise contaminated material around the time of the crab die-off may be evident in the 2022 survey around the Tees. Dog Whelks are surveyed and categized under an OSPAR classification of category A (best) to category D (worst). Overall, the picture in the UK has been one of declining imposex after the banning of TBT apart from a few hotspots around more heavily used harbours and ports. For context, in 1992 no sites in the UK were categorised as category A. During the 2022 survey of 55 sites around England and Wales, 17 sites were classified as category A and 38 sites as category B. Twenty-nine sites had shown an improvement in OSPAR rating since the last survey, 22 had remained the same, however, 4 sites had seen a reverse trend (Hanover Point, Llanbadrig, Moelfre, Hartlepool). Noteworthy was Hartlepool moving from a category A (<30% imposex) to category B (30-100% imposex), however, this site was not surveyed in 2018 to fully understand the timing of the exposure. Dog Whelks live about 5 to 6 years and the condition is irreversible so exposure would have been within that window. At 7 locations the biomarker for vas deferens development (VDSI) in female snails had increased indicative of greater TBT exposure but not sufficient to increase an OSPAR scale. Noteworthy, among those 7 were Scarborough, St Marys Lighthouse just north of the Tyne and Hartlepool which needed an increase in OSPAR scale. The conclusions from the Cefas report that these sites experiencing elevated imposex “could reflect higher recent dredging activity causing re-suspending sediment and increase discharge”.

The case of TBT highlights the potential for increased pollution due to increased mobilisation of sediments within the past 5 to 6 years. It is, however, *very unlikely* that the levels of TBT causing imposex were responsible for large crustacean die-offs within the Teesside area.

5.3 The case of pyridine

Pyridine has been identified as a possible causative agent due to its presence in crab tissues from the affected area. Furthermore, there is evidence of historical pyridine production (intentional and as a waste by-product) and with subsequent sustained release (alongside pyridine derivatives) to the Teesside estuary and associated coastal areas (up to 2021).

5.3.1. Environmental measurements of pyridine

Low concentrations of pyridine (0.05 to 2.4 μg/L) were measured in seawater through EA water monitoring conducted in the 2012 to 2018 period prior to the mortality incident in autumn 2021. Using a robust/validated water analysis methodology the EA could not detect pyridine in water or sediment samples during the incident period (October to December 2021). Subsequent collection of water and sediment samples in 2022 by York University revealed that pyridine was not detectable in water but was present in surficial sediment samples along the Tees Estuary with concentrations ranging from non-detect to 42 μg/kg (n = ~25, 12 locations with samples collected in the top 1 to 20 cm of sediment depth). Note that sediment concentrations reflect both pore water and particle-sorbed concentrations. Pyridine is not a persistent chemical but is water soluble (miscible with water) and hence mobile. Pyridine does not partition strongly to mineral surfaces or organic matter within sediments. It is unlikely to persist in sediment pore-water (even under anoxic/hypoxic conditions) at substantial quantities over a long time period (for example months to years). Pyridine like many organic solvents has a very strong odour due to its high volatility (with an odour threshold in water of 0.95 mg/L (Amoore & Hautala, 1983), compared to acetone of 20 mg/L). Any release of substantial quantities of a solvent like pyridine (>10,000 L) over a relatively short time (hours to days) might be widely noticed in populated coastal areas.

5.3.2. Industrial sources of pyridine

Pyridine use as a feedstock chemical in the fine-chemicals industry and arising as a contaminant by-product in a range of industries (many historical) located in Teesside and Redcar is reasonably well known. In recent years, fine-chemicals production (Vertellus) located near Seal Sands resulted in wastewater from this site containing residues of pyridine in the range of ~20 to 1000 mg/L, where 1000 mg/L is considered an exceptionally high residue content. This wastewater was tankered or delivered by pipeline (~33 m^3/day, yielding ~0.6 to 33 kg pyridine/day) to the Bran Sands waste-water treatment works (WWTW), operated by Northumbria Water Ltd. Pyridine and pyridine derivatives are efficiently removed by microbial degradation under a variety of environmental conditions typically encountered in soils, sludges and natural waters, with environmental persistence or residence time considered on the order of days (for example Sims et al., 2009). During effluent treatment, biodegradation is a key part of the secondary treatment process, where pyridine is effectively removed. Therefore, pyridine release to coastal waters through final treated effluent is considered insignificant. Further to this, the industrial sites that collect wastewater for transfer to Bran Sands WWTW use systems that have been designed to exclude storm water so the volume of treated effluent discharged is not influenced by high rainfall.

In addition to deliberate use of pyridine, this chemical can be generated as a by-product of other industrial processes. In the Teesside area there have, historically, been a number of industrial processes that will have resulted in the formation and release of pyridine along with many other volatile (and semi-volatile) by-products. Example industries include coke production (from bituminous coal) and the large iron and steel works.

Sahaviriya Steel Industries UK Limited (SSI) operated the Teesside Integrated Iron and Steel works on the south bank of the Tees Estuary until it ceased operations in 2015. Any excess or unwanted by-products as liquid waste was treated in either an onsite effluent treatment plant, prior to its consented discharge into the Tees, or transferred for third party treatment (for example Northumbria Water's WWTWs). Surface water collection for SSI would have been significant and subjected to assessment (for priority-list substances) prior to release from holding tanks into the estuary during receding tides. Pyridine was not screened for as it would have been deemed insignificant. Samples were taken of the discharge from the SSI site during the initial pollution investigation in the autumn of 2021 and pyridine was not detected. This site is now 'Teesworks' and is subject to a local enforcement position (LEP) for any residual discharge activity. The residual discharge activity and LEP ended in March 2022. Demolition of old industrial buildings, such as the

Redcar Coke Ovens, are highly unlikely to be significant sources of pyridine given the volatile nature of this chemical. Evaporative losses over time will now result in only trace levels possibly associated with residual bituminous coal or tars found around these sites.

5.3.3. Pyridine measurements and toxicity in crabs

Pyridine residues in edible-crab tissues were measured by the EA by adapting their water monitoring analytical method. This results in concentration measurements which are semi-quantitative but are relative given that all the crab material was analysed using the same laboratory method. Crabs were sourced from impacted and non-impacted sites in the Teesside and coastal region in the north-east of England, as well as crabs from Penzance, Cornwall, and the Norfolk Wash. Concentrations ranged from 3 to 195 mg/kg (Cornwall, Norfolk and 'non-impacted' NE) and 20 to 439 mg/kg (Teesside 'impacted'). Pyridine was measured in most samples regardless of location, which suggests that pyridine is an endogenous substance possibly formed during decay of soft tissue (see points above) although the highest concentrations were found in the impacted Teesside crabs.

In response to the die-off incidents, Newcastle University conducted an acute toxicity assay for pyridine exposure to the edible-crab (*Cancer pagurus*) and generated an LC_{50} (72 hours exposure) of 2.75 mg/L (Eastabrook et al. 2022). As a comparison, an LC_{50} (72 hours) value of 50 mg/L was established for sand shrimp (*Crangon septemspinosa*) in a separate international study (McLeese et al., 1979). A recent toxicity assay of pyridine exposure to the Common shore crab (*Carcinus maenas*) conducted at the University of Portsmouth (Giraud and Ford, 2023 - unpublished) could not establish an LC_{50} (meaning no mortality over 96 hrs) at µmolar exposure concentrations (1 to 1000 µg/L). These toxicity assays indicating different sensitivities to pyridine for different crustacean species. Exposure to pyridine at concentrations >10 mg/L for 24 hours (or longer) are likely to result in substantial mortality for crustacea in general.

5.3.4. Likelihood that water column concentrations of pyridine could cause crab mortality

Published modelling of chemical dispersion of pyridine from a source in the Tees (Eastabrook et al., 2022) demonstrates the potential distribution of this toxin, particularly to the south of the port. This modelling was based on release of large volumes of pyridine (10,000 L at two sites, or a total of 19.6 tonnes). The panel considered this modelling and considered it deficient in two aspects: 1) an unrealistically large volume of substance was injected into the model simulation, and 2) the model was approximately a factor of 10 more dispersive than most comparator observational estimates of coastal dispersion. Further modelling with more realistic source and mixing terms would be beneficial in the future. Never-the-less the existing modelling gives some assessment of concentrations in the water column. Even with the large input of pyridine, the modelling demonstrates that pyridine concentrations in the water column are too low to cause mortality in crabs**.** For example, the highest concentration range of pyridine modelled in a seawater plume from both the dredged area of the Teesmouth and the spoil disposal site was between ~1 to 10 µg/L. That is ~6 to 60-fold lower than the estimated 72 hours LC_{10} value for edible crab and ~2000-fold lower than the estimated 24 hours LC_{10} value (reported by Eastabrook et al., 2022). While the pyridine modelling was undertaken to illustrate the geographical spread and duration of a potential plume rather than representing the absolute concentrations, it is evident that a very significant emission of pyridine (I.e. greater than >20,000 L) would be required to achieve concentrations in seawater close to those that resulting in acute toxicity. **Based on assessment of industrial sources of pyridine assessed above, the panel concluded it was *very unlikely* that any point-source of pollution could provide sufficient pyridine to cause the unusual crab mortality.**

The panel also considered the liberation of pyridine from surficial sediment in the Tees Estuary. Based on the 2022 pyridine concentrations measured in sediment samples (for example the highest concentration of 42 μg/kg) and the total dredged and disposed mass of sediment of ~150,000 tonnes ('Orca' vessel dredging period – see Section 6), a total of <10 kg (or <10.2 L) of 'released' pyridine at either the dredged area and/or the offshore disposal site could be released. This quantity is far too low to be toxicologically significant, even if this quantity of pyridine was retained in a stratified water layer, for example associated with an estuarine system.

The actual dredging process would involve the disturbance and mobilisation of a greater mass of material than was removed and placed at the offshore disposal site. This disturbance occurs through the effect of the draghead of the dredger on the seabed (not all material disturbed is sucked up the dredge pipe into the hopper of the dredger) and to a greater extent as a result of the overflow of water and fines from the hopper as the load (of sand and fines) in the hopper increases during the dredging process. Both these processes might contribute to release at the dredge site. Volumes of sediment processed in this way are discussed further in Section 6. This additional sediment processing is insufficient to increase the total mass of pyridine released from sediment disturbance, removal and dumping to be toxicologically relevant. **The panel therefore concluded that it was *very unlikely* that pyridine released from sediments could have caused the unusual mortality of crab in the region.**

5.4 Water run-off from shore

River flow and discharge from WWTWs can deliver chemicals to seawater, including nutrients and a range of pharmaceuticals, pesticides, and other chemicals with distributed use.

This run-off occurs around the country, and there is no *a priori* reason to expect run-off chemicals to differ in the Teesside region, nor during the period of unusual crab mortality. The panel noted, however, that initial observations of crab mortality occurred at the time of a storm in the region (5 to 6 October 2021), and were sometimes associated with reports of sewage smells or debris. Although high rainfall and storm overflow can result in release of municipal untreated sewage (not industrial), at the time of the initial investigation in October 2021 there were no accidental or unauthorised discharges from the Bran Sands WWTW reported to the EA.

The EA screened estuarine and sea water samples over the October to November 2021 period for a very wide suite of synthetic organic chemicals. The chemicals with the highest concentration (100s ng/L) are the human food sweetener sucralose and common pharmaceuticals like paracetamol. This indicates the influence of WWTWs on coastal waters (both treated effluents and any storm overflow). The concentrations of an array of pharmaceuticals (human and veterinary) as well as pesticides were very low (<1 to 10s ng/L) and in the range of observations for other estuarine and coastal areas in Europe and elsewhere (Branchett et al.2021, Bjorlenius et al. 2018). Of the pesticides, Fipronil (an insecticide commonly used as a flea treatment in pets), was detected in several of the water samples. Fipronil is toxic to crustaceans at concentrations in the low µg/L range (Al-Badran et al. 2018). Although detected in Teesside samples, it was never above the 1 ng/L limit of quantification (meaning it was >1000 times lower than required for toxicity).

The absence of any observed toxic chemical associated with run-off, and the lack of any reason for the Teesside reason to have higher levels of such chemical run-off than other settings across the UK, led the panel to conclude that it is ***very unlikely*** **that chemicals associated with run-off from shore caused the unusual crustacean mortality.**

6 Dredging

6.1 Context on dredging

In dynamic estuaries and coastal areas, many ports and harbours need to dredge to provide and maintain safe navigable depths. **Capital dredging** generally excavates geological or historically accumulated sediments to create a new or deeper channel or berth. **Maintenance dredging** removes recent infill material to provide safe operating conditions in the context of the original or 'declared' channel (or berth) depth.

6.1.1. Capital dredging

The CMEP is not aware of any capital dredging being undertaken in the period leading up to this unusual mass mortality event. The port advises that the last capital dredging took place from September to December 2020 (Able UK's deepening of Able Seaton Port berths, holding basin and Seaton Channel). Capital dredging at Teesworks did not commence until September 2022, nearly a year after initial observations of unusual crustacean mortality. The Port Authority confirmed these dates, and that there was no reported capital dredging between December 2020 and September 2022. **The panel therefore considers it *exceptionally unlikely* that capital dredging on the Tees caused the unusual crustacean mortality seen in this region between these dates.**

On that basis, capital dredging is not considered further in this report.

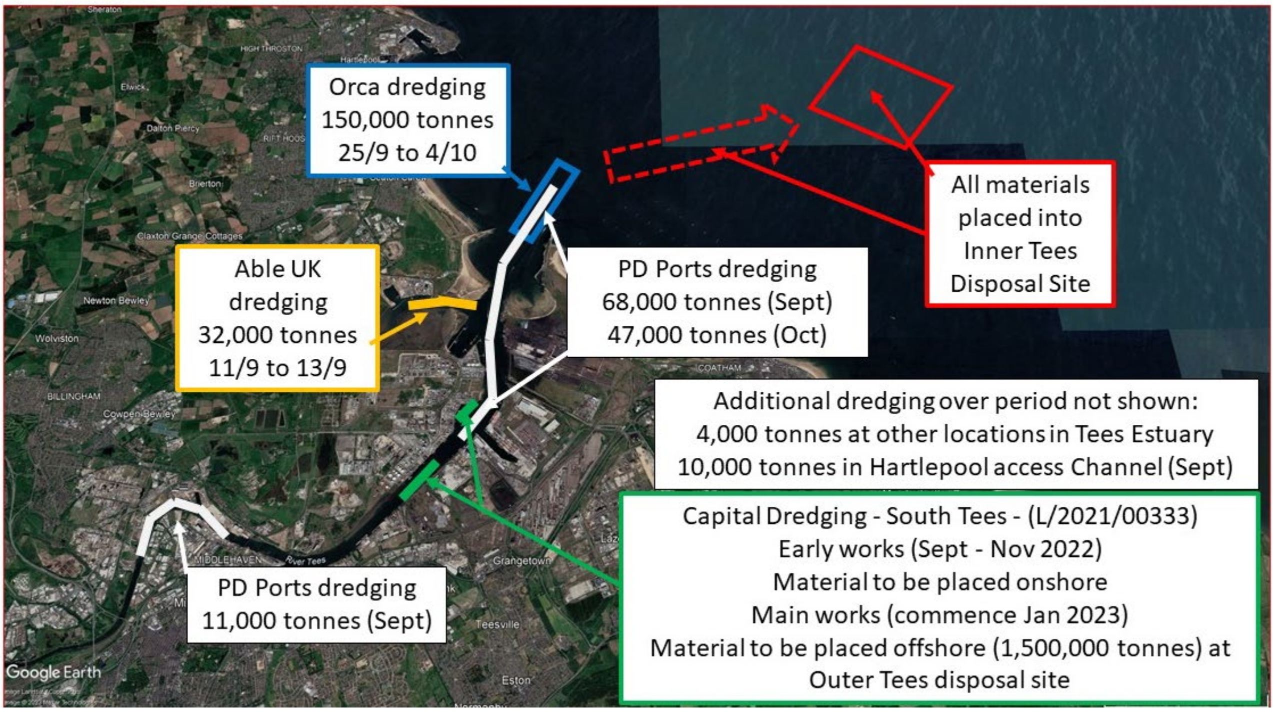

Fig 7: Map indicating the areas of maintenance dredging and disposal discussed in the report and occurring during September to October 2021. The map also shows, in green, the capital dredging undertaken later in 2022 and planned for 2023 (basemap from Google Earth).

6.1.2. Maintenance dredging

Sedimentation in the navigable areas of the Tees Estuary, including the offshore approaches, is a well-established phenomenon. The supply of sediment to these areas is influenced by wave action offshore in Tees Bay, and in years with more storms there is a greater sedimentation in the port areas. Storm waves mobilise both sand and fine sediment (silts and clays) from the offshore seabed and the largest storms can influence the seabed in water depths of up to 25 m. Nearly all of the sediment that is dredged from the Tees Estuary enters the estuary, and its inshore approaches, from offshore. Freshwater inputs from upstream bring a small proportion of silts and clays into the estuary.

In common with other UK port and harbour authorities, Teesport has a statutory duty to ensure safety of navigation, including maintaining sufficient depth of water for the vessels using the port. The management of sedimentation therefore involves regular bathymetric surveys of the estuary and sea bed in the navigable areas, and the development of a maintenance programme identifying where dredgers will operate to maintain the declared depth assuming typical accumulation rates. However, the port also needs flexibility to respond to less predictable sedimentation events, for example, re-establishing depth in the entrance channel following infill associated with a stormy period.

PD Ports and its predecessors have operated their own fleet of small dredgers to manage the maintenance dredging of the navigable areas for many decades. Dredging by the

Teesport dredgers (Cleveland County and Heortnesse) currently occurs throughout the year and throughout the estuary. The Port Authority divides the navigable areas of the port into 12 areas for the purposes of managing their maintenance dredging (see annex D.1 for further details of maintenance dredging areas).

Port Authority hydrographic surveys undertaken in June to September 2021 had identified an accumulation of sediment in Chart Areas 10 to 12, particularly in Area 11, arising as a result of storm activity over recent years including the February 2018 'Beast from the East' (see annex D.1 for details). Notwithstanding the activities of the port's own dredgers during the summer of 2021, it became clear that this backlog of sedimentation needed to be removed before possible further storms in the winter of 2021 to 2022. PD Ports' own dredgers would normally manage this infill but they had been subject to periods of planned and unplanned maintenance and one of them, the Heortnesse, was to be out of service from 1 October. The dredger 'Orca' was therefore commissioned to clear this backlog. (Annex D.2 for details on Orca dredging times and locations).

The CMEP focused particular attention on the activity of the visiting dredger, Orca, because she was undertaking maintenance dredging in the approach channel in the ten days immediately preceding the onset of the observed mass mortality event. This is the focus of Section 6.2.

During the period in question, there was also continued routine maintenance dredging by the two Teesport dredgers. In September 2021 both the Teesport dredgers were operational carrying out maintenance dredging and dredged a total of about 92,000 tonnes. Most of this dredging took place in Chart Areas 7 to 11 although around 10,000 tonnes were removed from further upstream in Areas 1 and 2, and10,000 tonnes from the Hartlepool Approach Channel. In October 2021 the Heortnesse was out of service (from 1 October to 3 December inclusive) so only the Cleveland County was operational. This dredger removed around 48,000 tonnes, primarily (more than 90%) from Area 9.

6.2 Characteristics of dredge location and the material dredged by the Orca

The sedimentation that occurred in the seaward part of the channel that was removed by the Orca dredger was not the result of a slippage. Rather the pre-dredge survey confirms it was the remaining backlog accumulation not yet cleared by the port's own dredgers. This is confirmed by the pre- and post-dredge surveys (see Figure 10 in Annex D.3). It is not clear to the Panel why the port representative referred to a slippage in evidence to the EFRA Committee to describe this backlog (the port has subsequently advised that a slippage comprising a run of sand did occur on 8 October in the vicinity of North Gare Sands, that is about a mile upstream of where the Orca had been working).

The post-dredge survey indicates that the accumulation of sediment removed by the Orca was typically towards the edges of the channel over the Chart Areas 10 to 12 (mainly Chart Area 11, Figure 8). The Orca maintenance dredge thus restored bed levels in the channel from pre-dredge levels of up to –14.1 m Chart Datum (CD) at the edges of the channel to post-dredge levels of at least –14.6 m CD.

As part of the licensing process for maintenance dredging disposal, Teesport must regularly characterise both the nature and the quality of the material to be dredged. Surface sediment samples are obtained and sent to an accredited laboratory for testing. The sample locations are agreed with MMO, and Cefas their advisors, which consider previous test results and the physical characteristics of the area.

Sediment analyses from August 2019 and from October 2021 both indicate that sediments accumulating in the channel bed in Chart Areas 10, 11 and 12 are very likely to comprise sandy material with a fines content of about 25 to 35 %. Furthermore, the underlying sediments in this inshore area (underneath and in the vicinity of the approach channel maintained by the Orca) are a mix of sand, gravel and stiff boulder clay (Burdis et al., 1967; Royal Haskoning, 2020).

If there were to be a slippage on the slopes of the dredged channel, it would therefore comprise of granular sand or gravel. There are no historic accumulations of potentially contaminated, anoxic, fine sediments. There are no muddy materials associated with industrial activity over the last century; and there are no sedimentary materials slumped from adjacent land exposed to such industrial activity. Material dredged was all recently accumulated sediments (Annex D.3 for details, and Section 5.3.4 for calculations of potential pyridine release from sediment).

Given the recent nature of the sediment infill and its mobility it is *exceptionally unlikely* that a reservoir of toxic contaminants (such as pyridine) exists or existed beneath or adjacent to the surface sediments disturbed and removed by the Orca's maintenance dredging activity.

6.3 Potential impacts of the sediment plume from Orca dredging

During the dredging undertaken by the Orca in September and October 2021, disturbance of the sea bed within the approach channel would take place along the full length of the dredge path (annex D.2 Figure 9).

Due to the size and duration of activity of the Orca, the plumes generated during the maintenance dredging undertaken were likely to have been more intense, particularly in Chart Area 12, than those formed when the PD Ports dredgers operate in the offshore part of the channel. However, the total mass of fine sediment released by the dredging is modest in comparison to the quantities potentially resuspended naturally during storm conditions in Tees Bay. **No mechanism can therefore be identified whereby the elevated levels of suspended sediment resulting from the maintenance dredging activity could have caused or contributed to the unusual mass mortality event.**

The plume formed from the dredging by the Orca would be expected to mix throughout the water column as a result of the turbulent mixing processes induced by the passage of the dredger through the water, the action of the drag head, and the recent overflow (see annex D.5 for further details about how a dredger operates). This plume will then advect from the dredge location under the influence of tidal currents before diffusing/dispersing (see annex D.6). On the flood tide the currents in the offshore part of the channel as dredged by the Orca are towards the south and south-east. On the ebb tide, they are towards the northwest. The spring tidal excursion (the maximum distance away from the channel that the plume might move on a spring tide) is about 5 km. The excursion will be proportionately smaller on mean and neap tides. The residual movement of a plume from tide to tide will be towards the southeast so it is unlikely that there are tidal mechanisms for the sediment plume and any associated effects advecting beyond Hartlepool to the nortwest. This conclusion, which corresponds to the modelling reported in Eastabrook et al (2022), indicates the likely extent of the dredged sediment plume.

6.4 Potential impacts of the disposal process

Despite the low concentrations of pyridine observed in sediments, CMEP also considered the possibility for release of pyridine during disposal of dredged material.

The management plan for the use of the Tees inner disposal site (see Figure 7) splits the site into 12 separate areas where disposal is to be focused each month to avoid mounding of material at one location within the disposal site. Over the period 2006 to 2019 the typical quantities of material disposed in September and October are reported to be about 135,000 m^3/month. When combining the activities of the Orca and other dredgers the rates of placement at the disposal site would be above average for September 2021 but less than average in October 2021. (7 describes modelling of the disposal).

Eastabrook et al. 2022 modelled the expected plume resulting from a large release of pyridine (as discussed above in Section 5.3.4). CMEP review of this modelling suggests use of an effective horizontal diffusivity of ~500 m^2s^{-1}, approximately a factor of ten greater than observational studies of dispersion over similar time scales of a few days. A more realistic horizontal diffusivity would substantially reduce the geographical distribution of the plume, but result in greater concentrations close to the site of disposal. In such conditions, the LC_{10} levels for edible crab could be reached but only in the immediate vicinity (meaning at not more than a few hundreds of metres) and only in the presence of an unrealistically large release of pyridine. Furthermore, the plume modelling does not provide a full representation of the source terms in respect to time. The dredging source term might be reasonably continuous for say 2.25 hours out of every 4.5 hours moving back and forth across Chart Areas 10, 11 and 12, but the disposal source would be at different locations across the disposal site occurring for about 0.25 hours out of every 4.5 hours.

Based on these considerations the CMEP considered it *highly unlikely* that disposal of dredged sediment could lead to the widespread mortality observed.

The Eastabrook et al. (2022) modelling indicates that water moves to the south and east along the coast from the mouth of the Tees, and gives an indication of speed. The first suggestions of crab being washed ashore were on Bran Sands (inside Tees Estuary mouth, to the south) on 4 October, before the storm that started on the night of the 5 October and ran for 12 hours into the 6 October. EA staff and IFCA staff visited various parts of the shoreline from the 8 October onwards and found significant numbers of crustacea washed ashore from Bran Sands and Greatham Creek in the estuary and Redcar and Seaton Carew Beach to the north and south of the Tees entrance. If reports of significant stranding of moribund crustacea prior to the storm are correct, it is possible that morbid crustacea are themselves moved southward in this flow.

6.5 Summary of dredging as a cause of crustacean mortality.

The absence of any capital dredging in the area between December 2020 and September 2022 **make it *exceptionally unlikely* that capital dredging is responsible for the unusual mortalities commencing in October 2021.**

Maintenance dredging by PD ports dredgers, and by Able UK, during September and October 2021 was part of normal long-term dredging and moved relatively small amounts of sediment from areas routinely dredged. There is no evidence that this dredging differed from that in previous months and years, and no evidence that it dredged material with an unusual concentration of toxic chemical. **It is *very unlikel*y that this routine maintenance dredging contributed to the unusual crustacean mortality events**.

The presence of the visiting Orca, conducting maintenance dredging in the offshore channel, removed sediment more intensively given its size and continuous operation. The sediment it dredged was reworked mainly sandy material recently moved into the channel by storm activity. The mobile and recent nature of the sediment dredged by the Orca make it *very unlikely* that this dredging, or subsequent offshore disposal, could have released any toxic chemical (including pyridine) at the volumes required to contribute to the unusual mortality event. **Overall, the possibility that maintenance dredging contributed to the unusual mortality is *very unlikely*.**

The higher-than-normal sediment dispersion from the offshore dredging is modest compared to that mobilised during storms and not considered a contribution to the unusual mortality.

7 Combination of factors

In is possible that a combination of factors lead to the unusual mortality, rather than one of the causal factors considered in this report. CMEP considered such possible combinations, including the possibility that several factors (for example a HAB, higher coastal run off, and higher sediment loads) might together combine to lower oxygen levels in the area. No particular combination of factors was identified that might be particularly likely to cause the mortality events. This does not rule out some combination of factors as a possible cause for the mass mortality; it is well-known that multiple stressors can be deleterious to ecosystems or individual species.

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Annex A – Requests for input from those outside the CMEP membership

During the CMEP's investigation they needed access to all the available data from the incident. The table below details an outline of the data requested by the panel.

Stage of investigation	Data requested
Initial investigation	• All the data held by M&F on the event. • A brief overview timeline of the incident with key dates and events.
Northeast university research group research	• Unpublished data from the group's research. • Measured pyridine concentrations in affected/unaffected crabs. • Any new findings relevant to the panel's investigation. • Sediment transport simulations
Wash up locations	• Details on locations of the deaths. • Dates of wash ups, numbers, locations, species, observed symptoms. • Observations offshore, videos and photographs. • Wash up logs extending to December 2022. • Confirmation of how far north the crab washups were reported.
Species data	• The species impacted. • What other species washed up with any unusual death at species level. • Indications of numbers involved. • Clarification on octopus findings.
Disease	• Which parasites were molecular screened for in samples. • List of diseases screened for using molecular approaches. • If amoebic disease could be ruled out. • Information on the testing from the live crabs. • If it is conceivable that it is a novel pathogen/virus not picked up in histological screens
Imposex	• Monitoring data for the area around the Tees

Stage of investigation	Data requested
Inshore Fisheries and Conservation Authorities observations	• Details on crab declines in other areas of the UK
Algal bloom	• Plankton data count for the *Karenia* data from Beadnell Bay • Source of satellite imagery. • Clarification on cell count measurement values. • O2 values in the area at the time. • Individual satellite images, as opposed to a composite image from Berwick to Runswick Bay. • Phyto counts from Berwick to Runswick Bay. • Extending imagery and *Karenia* counts to Stonehaven, east Scotland. • Clarification of *Karenia* risk from PML report.
Pyridine	• Presentations on pyridine results. • Details on pyridine environmental concentrations • Measured sediment associated pyridine concentrations. • Pyridine analysis from Portsmouth university.

Stage of investigation	Data requested
Dredging activity	• Timing and location of dredging activities. • Environmental impact assessments including the Maintenance Dredge Protocol • Characterisation of the dredged material disposal site. • When the slippage occurred. • What the slippage material was in the area being dredged, that is normally well mixed material or previously undisturbed sediment. • Channel bathymetry before and after dredging. • Why the whole channel was dredged rather than in the immediate area of the slippage • Ship track data of the regular maintenance dredger – request rescinded. • Typical duration of overflow when the Orca was dredging and how it compares with the PD port dredgers. • How many dredge pipes the Orca dredger was using. • Clarification on other dredging activities in the port at the time. • Chemical analysis of samples obtained after dredging activity. • When the approach channel was last dredged to -15.4m • Location of the capital dredging and dates.
Infrastructure capital works	• Detail on other marine infrastructure capital works going on in the east coast of Scotland and the north-east of England at the time.
Discharges	• Details of any large sewage discharges or unusual rain events. • Information on Vertellus operation dates and if there was a licensed discharge from the site at the time. • If there was a deliberate or accidental release from the Bran Sands wastewater treatment site at the time. • More detail on licensed discharges due to high rainfall at the time across the area impacted. • Information on the coking plant that was being decommissioned including when it was destroyed.

Stage of investigation	Data requested
Vessel activity	• List of vessels carrying/capable of transporting bulk liquids, particularly solvents, surfactants, caustic/liquid chemicals, entering or leaving the port authority area during the last week in October 2021.

Annex B – Conflict of Interest

The following conflicts of interest were declared by CMEP members.

Name	Declared Conflict of Interest
Gideon Henderson	Defra’s chief scientific adviser has had no previous exposure to this issue and is independent of previous government consideration of crustacean mortality.
Eileen Bresnan	I am a member of the UK Pelagic Habitats Working Group and have received a small about of funding from DEFRA as part of this group to participate in the development of tools and indicators to assess the status of the plankton community for the UK Marine Strategy.
Jan Brooke	I work with ports industry elsewhere in the UK and in Europe providing independent expert environmental advice. I do not work with ports in the north-east of England. The nature of my work necessarily means I work closely with organisations that are involved in other areas.
Keith Davidson	I have recently joined the UK Pelagic Habitats Expert group that is in receipt of DEFRA funding. The phytoplankton component of the Scottish biotoxin producing phytoplankton monitoring programme, of which I am the scientific lead is operated by SAMS Enterprise for Food Standards Scotland (FSS). SAMS Enterprise subcontracts this work from Cefas who lead the monitoring programme as a whole.

Name	Declared Conflict of Interest
Mike Dearnaley	I work for HR Wallingford, an independent research organisation. The Company has a long history of involvement in UK Ports including the Tees. Over the years I have been involved in research and consultancy projects on the Tees which have been funded by the ports industry and by government. This work is of relevance to the matters under consideration by the panel relating to dredging and coastal processes.
Mark Fitzsimons	None raised
Alex Ford	Worked on the effects of pyridine and linked to a project which looked at dredging impacts on crustaceans in which pathology samples went to Cefas, asked by press in Teesside deaths. Has had several communications with Dr Caldwell and staff from Cefas and the EA – but not worked directly with them.
Tamara Galloway	None raised
Crispin Halsall	None raised
Tammy Horton	None raised
Mark Inall	None raised
Marian Scott	None raised
David Wilcockson	In receipt of Defra funds for looking at windfarms and lobsters

Annex C – Abbreviations

ACD	Amoebic crab disease
CD	Chart datum
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CHASM	Crustaceans, Habitat and Sediment Movement
CMEP	Crustacean mortality expert panel
CSA	Chief scientific adviser
DO	Dissolved oxygen
EA	Environment Agency
EFRA	Environment, Farming & Rural Affairs
EIA	Environmental impact assessment
FSA	Food Standards Agency
FSS	Food Standards Scotland
GCSA	Government chief scientific adviser
HAB	Harmful algal bloom
IFCA	Inshore fisheries and conservation authority
IPCC	International Panel on Climate Change
LC50	Lethal concentration (concentration required to kill half of a test population)
LC10	Lethal concentration (concentration required to kill 10% of a test population)
LEP	Local enforcement position
LOD	Limit of detection
MMO	Marine Management Organisation
NOC	National Oceanography Centre
OSPAR	The Convention for the Protection of the Marine Environment of the North-East Atlantic
SAMS	Scottish Association for Marine Science
SCObs	Scottish Coastal Observatory
SSI	Sahaviriya Steel Industries UK Limited
TBT	Tributyl Tin
WSSV	White Spot Syndrome Virus
WWTW	Waste water treatment works

Annex D – Dredging

Annex D.1: Details on maintenance dredging areas.

Figure 8 shows details of the Tees Estuary and numbered dredging zones. Chart Areas 1 (upstream) to 8 (Redcar Bulk Terminal) typically have muddy sedimentation with a silt/clay content of more than 75%. In the Chart Areas to seaward (9 to 12) the sedimentation is predominantly sandy with a silt/clay content of 25-35%.

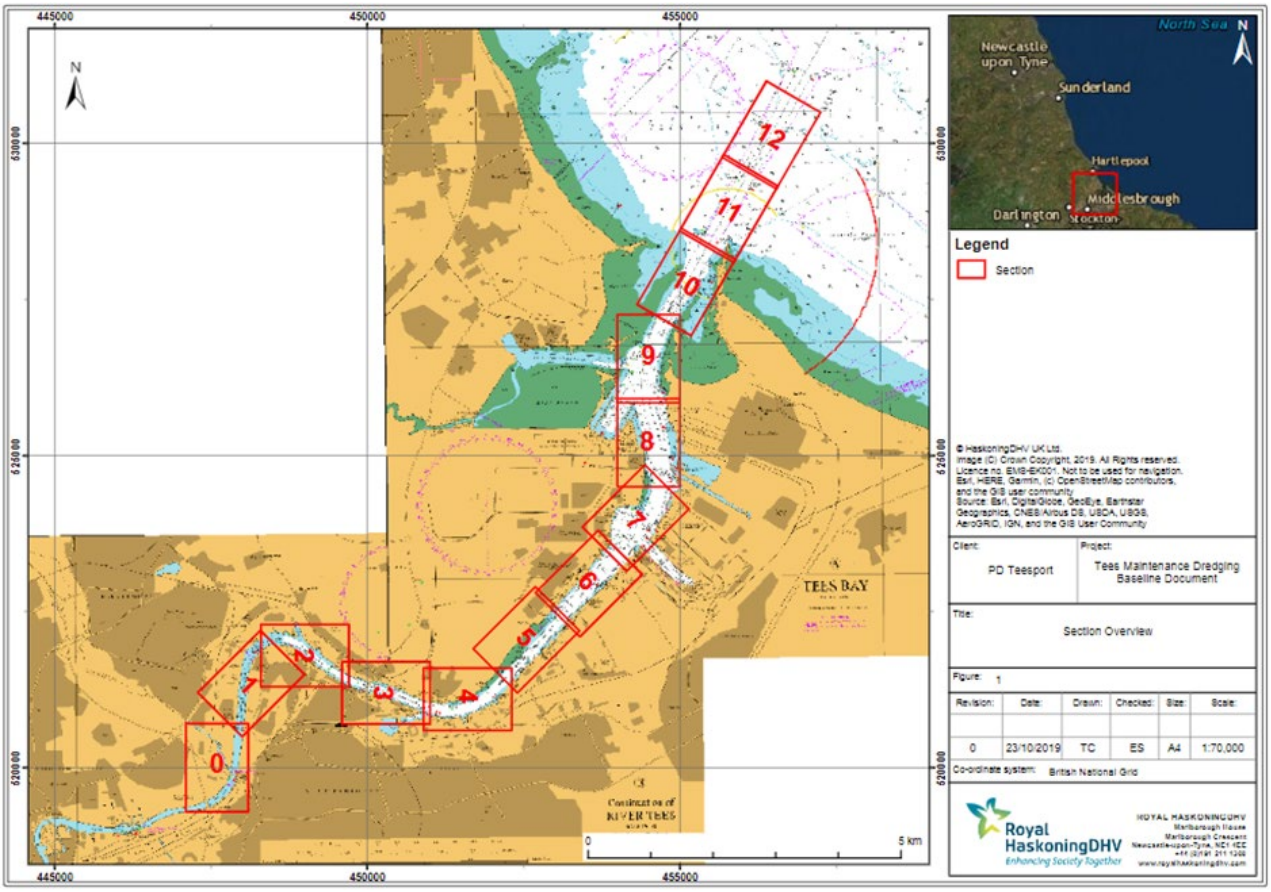

Fig 8: Map indicating the 12 areas defined for maintenance dredging (Reference 06-2ST Tees Maintenance Dredging 2019).

The intensity of dredging in a particular Chart Area will vary from year to year in response to the requirements of port users as well as weather conditions. In Chart Area 12 the volumes maintenance dredged between 2013 and 2019 ranged from about 5,000 to 11,000 m^3/year; in Chart Area 11 over the same period they ranged from 12,000 to 130,000 m^3/year; and in Chart Area 10 from 21,000 to 221,000 m^3/year.

Annex D.2: Details of Orca dredging

Figure 9 shows the positions of the Orca dredger during its operation in the Tees channel. Further details can be found in links within Eastabrook et al., (2022).

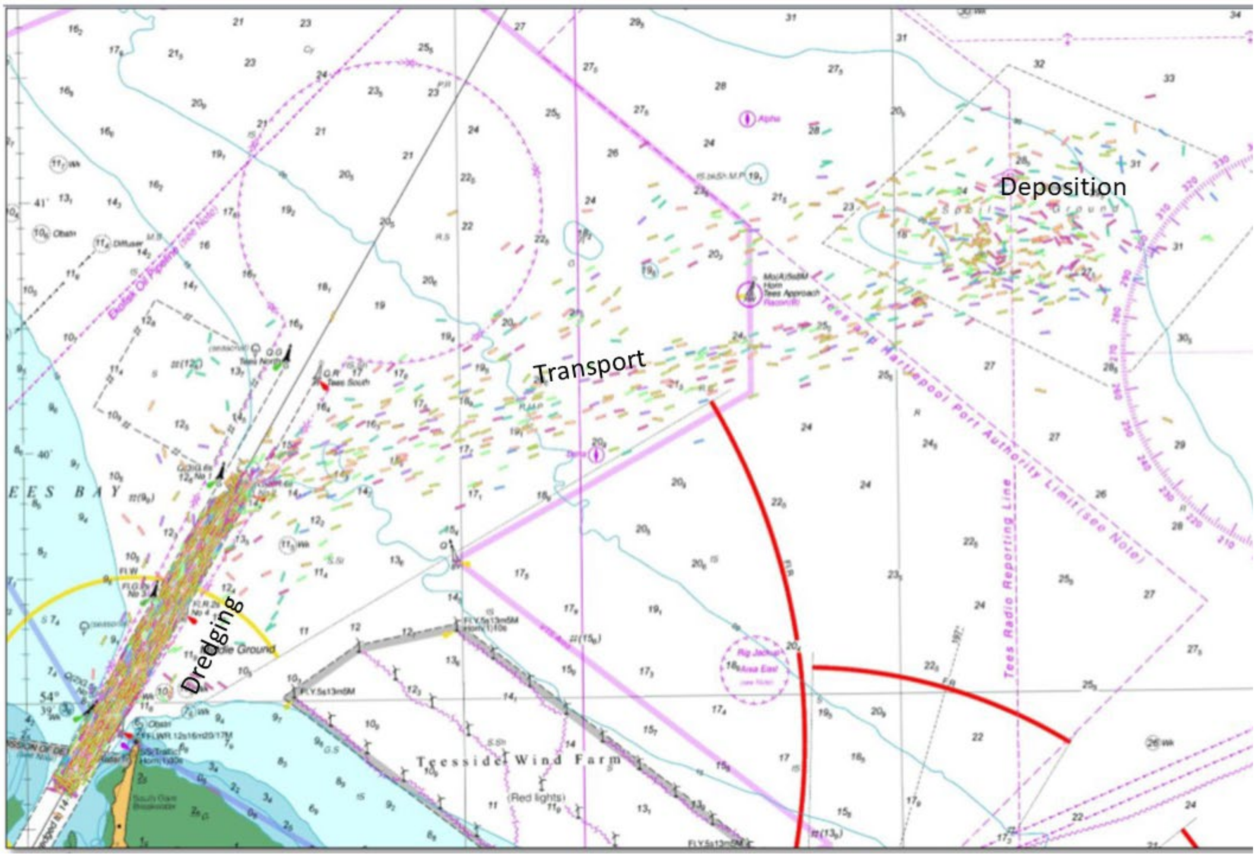

Fig 9: Compilation of the positions of the dredger over the period 25 September to 4 October every few minutes based on transmissions of it position using the AIS system. Dredging activity in the south-west and deposition site in the north-east.

The Orca dredger is a trailer suction hopper dredger (TSHD). It is a similar size vessel to the dredgers operated by PD Ports. However, it has a hopper of 2,373 m^3 compared to the PD Ports' TSHD Heortenesse hopper capacity of 1,500 m^3. The Orca has twin dredge pipes 700 mm in diameter and the Heortenesse a single pipe of 650 mm diameter. The Port has confirmed to the Panel that the Orca undertook the maintenance dredging using one pipe only.

The Orca dredger sailed from the Humber up to the entrance to the Tees Estuary and commenced the maintenance dredging at around 08:00 on 25/09/21 finishing at around 06:00 on 4/10/21. The dredger worked continuously, dredging over an approximately 3 km length of the entrance channel. The dredger typically made four passes back and forth over this area of the channel whilst dredging on each cycle. The average cycle time (including loading, sailing to the disposal site, disposal and return to the dredge site) was about 4.5 hours. In total the Orca dredged approximately 150,000 tonnes of sediment across Chart Areas 10, 11 and 12, much of this in Chart Area 11, over 52 cycles of dredging and disposal. N.B. This latter figure is notable insofar as it represents only 1% of the c.5000 transits of the dredger highlighted in the October 2022 North East Research Group Investigation Report as being needed to reach the threshold used in the pyridine plume modelling (NEFC et al., 2022).

Annex D.3: Details on maintenance dredging depth

The port authority has confirmed their maintenance dredging objective is, as far as practicable, to maintain the channel at better than –14.7 m CD, but not more than –15.4 m CD (the maximum depth of the dredged approach channel). They note that the outer part of the channel self-maintains at –15.4 m CD or better but that from approximately No 1 and No 2 buoys and into the estuary, natural processes lead to infill and maintenance dredging effort is focussed on these areas.

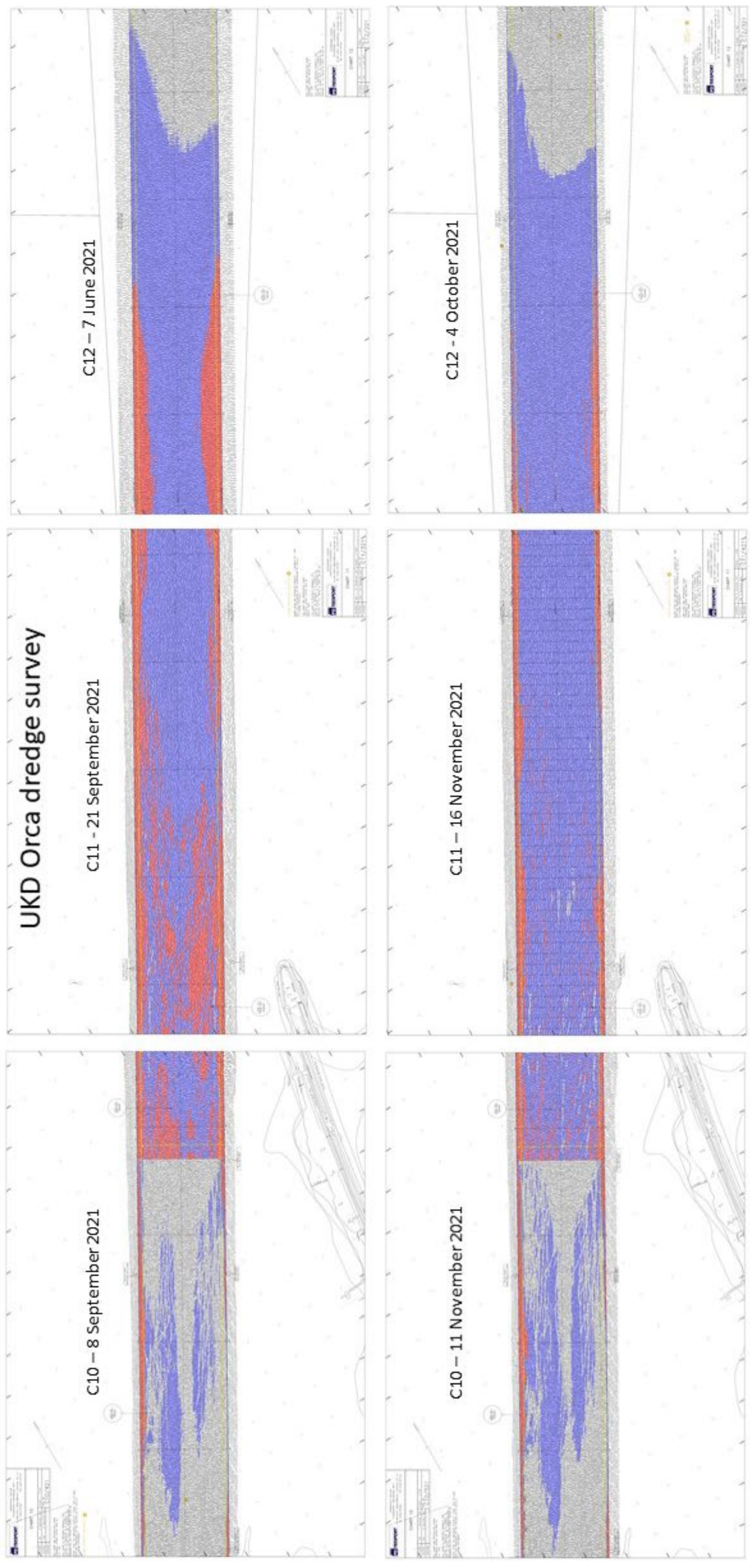

Fig 10: Pre dredge (left) and post dredge (right) surveys from PD Ports of Chart Areas 10, 11 and 12. Red areas indicate areas of shoaling within the channel.

The left part of Figure 10, provided by the port, shows the pre-dredge situation for Chart Areas 10 to 12 with the red highlighting the main shoal areas in the navigation channel that the Orca dredging was targeted at removing. The right figure shows the post-dredge survey demonstrating the removal of the shoals.

The Port was able to resurvey the seaward part of the area dredged by the Orca on 4 October after the dredging was completed. They could not immediately survey the inshore part of the area dredged because of poor sea conditions.

Annex D.4: Details of sediment sampling and disposal licensing

The present 10-year maintenance dredge licence for the area was issued in 2015. Prior to October 2021 dredging the MMO and Cefas had not required sampling of sea bed sediments and analysis of contaminants in the offshore part of the approach channel (Chart Areas 11 and 12). This was because historic sampling had shown that contaminant levels in the offshore sandy material were typically lower than those in the muddier material within the estuary. Licensing conditions required the sediment samples that were taken throughout the port on 13 October 2021. This included sampling in Chart Areas 10, 11 and 12. These samples showed that concentrations of contaminants in Chart Areas 10 and 11 were comparable to those elsewhere in the estuary. Contaminant concentrations in Area 12 were much lower by comparison.

Subject to the outcomes of such sediment sampling and analysis, the MMO advises on the suitability of dredged material for sea disposal based on the Cefas Action Levels and weight-of-evidence approach, and disposal licences are issued accordingly. Maintenance dredged material from Teesport that is deemed suitable for sea disposal is taken offshore and placed at the Inner Tees Offshore disposal site under licence (see Orca track figure 9). The site has been used for decades and has been subject both to research regarding the dispersion of placed material and to ongoing sampling to establish whether there is evidence of chemical contamination in and around the site. Over the period 2006 to 2019 between 0.5 to 1.5 Mm^3 of material has been placed each year at the disposal site. Disposal occurs in every month with quantities varying from averages of about 80,000 to 200,000 m^3/month.

Annex D.5: Detail of trailer suction dredger and plume creation.

A trailer suction hopper dredger operates much like a ‘hoover’, using a ‘drag head’ to suck up a mixture or sediments and water from the sea bed into a hopper. As sediment accumulates in the hopper, a mixture of water and fine sediment typically overflows (to ensure that the dredger operator does not transport a hopper full of water, rather than sediment, to the disposal site, which would both prolong the duration of dredging and significantly increase its cost and CO2 emissions). Impacts can arise from the maintenance dredging process at different stages: the disturbance of sediment and any associated contamination at the drag head; the resuspension of sediments via the overflow process; any associated release of contaminants during this process; the subsequent deposition of this resuspended material; and the equivalent impacts during the disposal process.

The overflow from the Orca dredger is directed through the keel (meaning about 4-6 m below the water surface as the vessel becomes laden). The plumes created by the dredging activity would be created over the full length of the dredge path as the dredger moved back and forth during the loading process. Annex D.6: Details of the sediment plume

The Orca dredging commenced on 25/09/21, a few days after spring tides and completed on 4/10/21 a few days before spring tides. The sea state during the dredging was moderate. A significant storm with waves heights offshore in Tees Bay of nearly 5 m occurred on the night of the 5/10/21. Given that the tidal currents were typically mean to neap tide currents the amount of advection and dispersion of the plumes from the dredging and disposal would have been smaller (on average) than if the dredging had occurred over a period including spring tides. This would result in elevated concentrations in the dredging and disposal plumes local to the dredge and disposal activity compared to average or spring tide conditions.

Differences in the behaviour of the plume are expected at the landward end of the area being dredged (Chart 10 and Chart 11) where the sea bed levels are at around –8 m CD and the dredged channel is therefore incised some 6 m into the sea bed. Here the morphology may confine the lower parts of the plume compared to the seaward end of the channel where the bed levels are closer to the level of the channel.

Suspended sediments in the plume will slowly settle to the sea bed (at typical velocities of 0.1 to 2 mm/s) subject to the influence of currents and wave action. In the shallow inshore waters adjacent to the landward end of the dredging, however, the combined effects of waves and currents will prevent fine sediment from the plume settling and accumulating on the seabed. The representation of a single release point for the source from the dredging plume in a model simulation will, depending on model grid resolution, lead to locally elevated predictions of suspended sediment concentrations and contaminants. During the flood tide a proportion of the plume formed by the dredging will be transported into the Tees Estuary, particularly from the landward part of the dredging. During the ebb tide the tidal discharge of the estuary will move the plume seawards. Accurate representation of these processes requires adequate resolution of the tidal exchange between the estuary and the coastal waters.

The plumes generated during the maintenance dredging undertaken by the Orca are likely to have been more intense, particularly in Chart Area 12, than those formed when the PD Ports dredgers operate in the offshore part of the channel. This is because of the larger size and power of the Orca as well as her continuous (24/7) operation in the same Chart Areas. The plumes formed by the dredging would therefore have resulted in elevated near bed suspended sediment concentrations over an area extending a few km from the dredging, including into the estuary mouth. The highest suspended sediment concentrations would have occurred closest to the dredging. The fine material suspended by the dredging process would tend to settle out to form a thin layer on the seabed with local patches of greater accumulation in hollows and depressions on the deeper parts of the seabed. In the shallower water wave action in combination with tidal currents would have prevented such formation.

As the dredging progressed the material released in the plumes would settle to the seabed (a mass conservatively estimated as 50,000 tonnes). The storms and spring tides of 5 and 6 October would have resuspended all the fine material released from the dredging activity that remained in the exposed coastal waters. This fine material associated with the dredging would have been mixed into the fine material resuspended from the wider seabed by the storm activity.

In order to determine how this resuspension from the dredging activity would compare to natural storm conditions, it is conservatively, assumed that the sediment in the Orca-generated plumes settled over an area of the seabed of about 10 km by 3 km and that the mass of fines released was about 25,000 tonnes. In this case, the deposited material would from a layer an average of about 3mm thick at a dry density of 300 kg/m^3. This sediment would then have readily been resuspended during the storm of 5 and 6 October. In addition to the veneer of freshly settled sediment from the plume, the storm would mobilise much of the seabed to depths of 0.1-0.2 m. Assuming the sea bed comprised an average of 5% fines at a dry density of 1,000 kg/m^3, then the effect of the storm over the area of the seabed influenced by the plume would be to mobilise a further 150,000 to 300,000 tonnes of fine material into the water column.

The total mass of fine sediment released by the dredging is modest in comparison to the quantities potentially resuspended naturally during storm conditions in Tees Bay. No mechanism can therefore be identified whereby the elevated levels of suspended sediment resulting from the maintenance dredging activity could have caused or contributed to the unusual mass mortality event.

Annex D.6: Sediment behaviour during disposal

During disposal activities at the Tees Inner disposal site, the dredger is near stationary. The doors of the hopper in the keel of the vessel are opened and the sediment and water in the hopper slides out of the hopper. Given the loose nature of the dredged material in the hopper (sand and water with some fines) the load does not simply fall to the seabed and form a mound, it is spread over a significant area of the sea bed forming an associated near bed layer/plume of high concentration of suspended sediment. This plume will then advect away from the disposal location under the influence of tidal currents and dispersion. Suspended sediment in this near bed plume will slowly settle to the sea bed (at typical velocities of 0.1 to 2 mm/s) subject to the influence of currents and wave action. The use of a single release point for the source from the dredging plume in the model simulation will, depending on model grid resolution, lead to locally elevated predictions of suspended sediment concentrations and any associated contaminants.