



Northeast Fisheries Science Center Technical Memorandum 443

Fish Injury and Mortality Events at the Coastal Virginia Offshore Wind Commercial Project in 2024

September 2026



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US DEPARTMENT OF COMMERCE

National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northeast Fisheries Science Center
Narragansett, Rhode Island
September 2026

Editorial Notes

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This document may be cited as:

Methratta, E.T., Jewett, E.B., Hall, M., Heimann, T., Horodysky, A., Lipsky, A., Scholik-Schlomer, A., Smith, A., Van Hoeck, R. and Weeks, R. 20 6. Fish Injury and Mortality Events at the Coastal Virginia Offshore Wind Commercial Project in 2024. US Dept Commer Northeast Fish Sci Cent Tech Memo 451. 39 p

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LIST OF ACRONYMS

BOEM – Bureau of Ocean Energy Management

BSEE – Bureau of Safety and Environmental Enforcement

COP – Construction and Operations Plan

CMECS – Coastal and Marine Ecological Classification Standard

CVOW-C – Coastal Virginia Offshore Wind-Commercial

DBBC – Double Big Bubble Curtains

ESA – Endangered Species Act

GARFO – Greater Atlantic Regional Fisheries Office

GBT – Gas Bubble Trauma

GW – Gigawatt

HMD – Hybrid millidecade spectra

LTSA – Long-Term Spectrogram Average

NAS – Noise Abatement System

NMFS – National Marine Fisheries Service

NOAA – National Oceanic and Atmospheric Administration

OCS – Outer Continental Shelf

PAM – Passive Acoustic Monitoring

PBT – PyPAM-based processing

PSO – Protected Species Observer

SPL – Sound Pressure Level

VA – Virginia

VIMS – Virginia Institute of Marine Science

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1. EXECUTIVE SUMMARY

In 2024, a series of fish kill events were observed at the Coastal Virginia Offshore Wind-Commercial (CVOW-C) project located 44 km off of the coast of Virginia Beach, VA USA during a period of project-related construction activities. Fish kills have not previously been reported in the peer-reviewed literature in relation to offshore wind construction activities worldwide. Observational data collected by protected species observers during the CVOW-C fish kill events indicate that approximately 18,000 fish were killed. The majority of dead fish were identified as Atlantic croaker (*Micropogonias undulatus*) and a smaller number were identified to be spot (*Leiostomus xanthurus*). Two separate opportunistic necropsies were conducted by independent institutions on 35 fish killed. The injuries identified by the necropsies included skeletal trauma, muscle damage, internal and external decapitation, deflated swim bladders, and intravascular gas bubbles within the gills. Neither necropsy was able to determine a definitive cause of fish mortality or injury based on the information available. The combination of injuries reported in the necropsies suggest that specimens may have experienced acute trauma prior to or during rapid ascent in water supersaturated with dissolved oxygen. Analysis of passive acoustic monitoring (PAM) data from PAM recorders located in the area found no correlation between changes in the acoustic environment and observations of the fish kills. Although the fish kills are suspected to be associated with construction activities, their specific cause is not known. Other activities that occur during the offshore wind construction process should be evaluated. In particular, the operation of the double big bubble curtain may have played a role and should be examined to determine its potential involvement in the mortality of affected species. The CVOW-C fish kill events were unexpected, and therefore, there were no plans in place for addressing such events at the time they occurred. There is a clear need to establish a standardized protocol that is incorporated into the terms and conditions of BOEM's approval of a developer's Construction and Operation Plan (COP) to address the potential for future fish kills associated with construction activities for offshore wind or other marine development projects on the outer continental shelf. The addition of a fish kill Monitoring and Response Plan included in future COP terms and conditions should detail when and how to collect, preserve, analyze, report, store, and share data associated with potential future fish kill events. A standardized established protocol will enable a better understanding of potential causes of these events and help to advance approaches for avoiding, minimizing, and/or mitigating future events.

2. INTRODUCTION

Fish injury and mortality (i.e., “fish kill”) events were reported in 2024 at two offshore wind projects in the Atlantic Outer Continental Shelf of the United States: the Coastal Virginia Offshore Wind-Commercial project, lease area OCS-A 0483 (hereafter referred to as CVOW-C); and at the Revolution Wind project, lease area OCS-A-0486 (hereafter referred to as Revolution Wind). This technical memo focuses primarily on the events at CVOW-C because this location experienced a higher number of events, involved a larger number of fish per event, and there were additional environmental and acoustic data available from this location to examine. The goals of this report are to: 1) document the injury and mortality events at CVOW-C and associated data collected in the area around the time of the events including necropsy and passive acoustic monitoring data; 2) describe existing protocols available to monitor and assess fish injury and mortality events; and 3) recommend a protocol for monitoring and assessment of fish injury and mortality during marine development construction activities. Although the fish kill events were observed during construction activities, this report does not attempt to attribute the causal mechanism(s) of the injury and mortality events because there is insufficient information to do so.

3. COASTAL VIRGINIA OFFSHORE WIND COMMERCIAL (CVOW-C) PROJECT

3.1 Project Description

CVOW-C is a 2.6-gigawatt (GW) project located 44 km from Virginia Beach, VA (Figure 1) that is being developed by Dominion Energy. Once completed, CVOW-C is expected to consist of 176 monopile turbines each with a generating capacity of 14 megawatts (MW) of energy. In 2024, 78 of the 176 planned monopile turbine foundations were installed within the CVOW-C project area. Installation of fixed monopile turbine foundations requires vibratory and/or impact pile-driving of the foundation into the seabed. The benthic habitat at the CVOW-C lease is primarily sandy bottom, and all monopile foundations installed to date have been in the following CMECS habitat classifications, “Coarse Sand/ Very Coarse Sand,” “Fine Sand/Very Fine Sand,” and “Medium Sand.” The water depth ranges from about 22 to 35 m. No apparent association exists between type of substrate habitat or water depth and the occurrence of the fish kills.

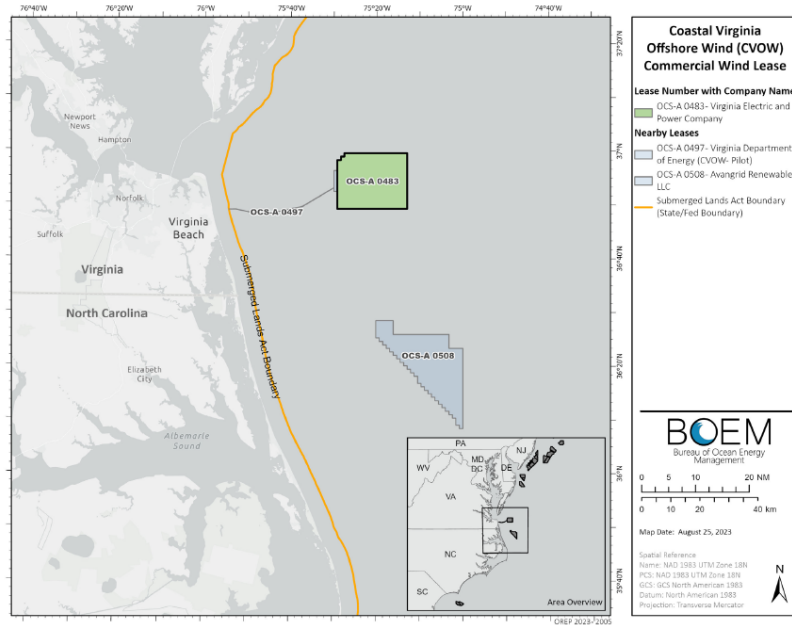


Figure 1. Map showing the location of the Coastal Virginia Offshore Wind Commercial project (CVOW-C) (green polygon). <https://www.boem.gov/renewable-energy/state-activities/CVOW-C>

3.2 Construction Activities

In 2024, pile driving occurred from May - September at CVOW-C. Bubble curtains were employed to mitigate the noise impacts associated with pile driving, which can reduce injury and noise levels for marine species (CalTrans 2020). For CVOW-C, the bubble curtains were deployed in two concentric circles (double big bubble curtains, DBBC) with radii of 85 m and 123.6 m. Holes for the bubbles were drilled in the tubes every 100 - 300 mm and were ~2 mm in diameter. The pressure of the air compressor was 10 bar, providing a free air delivery of 787.5 m³/min and an air flow rate of >0.5 m³/min/m. Proper functioning of the bubble curtain is confirmed by a sequence of flushing the hose and pressure testing that occurs after the bubble curtain has been deployed and before any other construction activities, including monopile pre-install, begins. Flushing of the bubble curtains prior to pile driving allows the air to clear the hose of any debris that has gotten into the holes while the hose has been sitting on the seafloor, while pressure testing allows the crew to check the curtain for weak spots. Weak spots can be seen by a lack of bubbles rising to the surface of the water and can be caused by blocked holes or twists in the hose. If the weak spot cannot be corrected by flushing the curtain, the hose is brought to the surface to inspect and piling is not completed at that time. The amount of noise attenuation achieved by a bubble curtain depends on a number of factors including the bubble density and the width of the bubble curtain (CalTrans 2015; Bellmann et al. 2022). Note that the DBBC remains active during pre-install, vibratory pile driving, switch (i.e., post-vibratory but pre-impact pile driving), and impact pile driving phases. In this paper, “construction activities” can refer to all of the steps associated with the pile driving process, including the operation of the DBBC (Figure 2). During construction

activities, a dynamic vessel positioning system (i.e., a shipboard system that employs sensors and thrusters to maintain a fixed position in the dynamic ocean environment) was used which may also generate bubbles in the water column.

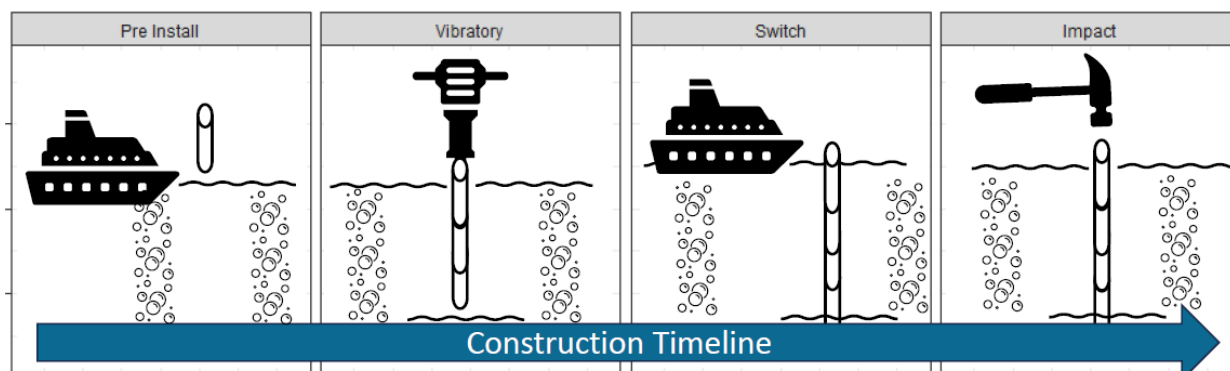


Figure 2. The DBBC is active during the pre-install, vibratory pile driving, switch (i.e., post-vibratory but pre-impact pile driving), and impact pile driving phases. Image courtesy of BOEM. Note that flushing and pressure testing of the bubble curtains occurs prior to the pre install phase.

3.3 Protected Species Observer Activities at CVOW-C During Pile Driving Activities

Protected Species Observers (PSOs) are required by the conditions of the BOEM approved Construction and Operation Plan (COP) to observe for protected species for set periods of time before, during, and after pile driving activities. Three PSOs at CVOW-C are assigned to each vessel which include an installation vessel and two support vessels (Figure 3). The support vessels travel in a circular path around the pile being installed with a radius of 3 km from the activity (Figure 3). Monitoring zones around project construction activities are determined using project-specific factors such as the type and strength of hammer (i.e., impact, vibratory) to inform modeling to predict distances at which protected species would be expected to be exposed to noise that could result in behavioral or auditory impacts to marine mammals and sea turtles. Thus, zones are not a standardized spatial area for all projects. Because fish do not surface to breathe, ESA-listed fish cannot be effectively monitored by PSOs. However, their presence is noted if visually observed. PSOs are primarily in place to document marine mammals and sea turtles and to call for the implementation of required mitigation measures which include delaying or shutting down pile driving operations in accordance with requirements outlined in the terms and conditions of COP approval, MMPA Incidental Take Authorizations (ITAs), and ESA Biological Opinions. Additionally, BOEM has required, through the Terms and Conditions of BOEM COP approval for all permitted offshore wind projects including CVOW-C, to report any occurrence of ten or more deceased individuals of non-ESA listed fish species within the shutdown or monitoring zones of

the project¹. PSOs are neither trained nor officially responsible for observing or recording data regarding non-ESA listed fish species; nevertheless, the PSOs at CVOW-C opportunistically observed and collected information on the fish kill events that are described in this report.

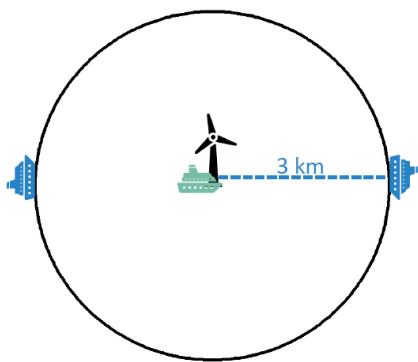


Figure 3. Protected species observations were made at CVOW-C by PSOs assigned to each of three vessels including the installation vessel (green) and two support vessels (blue). Image courtesy of BOEM.

4. CVOW-C FISH KILL EVENTS

4.1 Observation of Fish Kill Events

For the purposes of this report, an “observation” is a specific report from a PSO regarding a sighting of a specific group of dead and/or injured fish. Observations should be considered to be independent of each other unless they are made at the same time and in the same location by two different observers as indicated in the field notes. An “event” may consist of one or more observations that occur in association with a specific construction activity (e.g., impact pile driving of a specific monopile). A specific construction activity may have more than one event. The CVOW-C fish kills comprised 39 observations of dead and injured non-ESA listed fish species (Table 1) made by the PSOs. These observations were made at 24 different pile locations out of the 78 total piles (or 30% of piles) that were installed at CVOW-C in 2024 (Figure 4). Monopile foundation pile-driving began at the end of May and continued through September. Most observations of dead fish occurred in June and August, with one observation at the end of May. The observations occurred during different phases of construction activities and indicated that fish occurred at distances estimated to range from 0 m - 4000 m from the pile being driven (mean distance= 99 m - 3,038 m) (Table 1). The largest percentage of fish were observed during the pre-

¹ The Terms and Conditions of the CVOW-C COP approval, section 5.16.3.4 Detected or Impacted Dead Non-ESA-Listed Fish states that, “The Lessee must report any occurrence of at least 10 dead non-ESA-listed fish within established shutdown or monitoring zones to BOEM and BSEE as soon as practicable (taking into account crew and vessel safety), but no later than 24 hours after the sighting. BOEM or BSEE will notify NMFS GARFO. The Lessee must confirm the relevant point of contact prior to reporting and confirm the reporting was received.”

install (38%) and the switch phases (28%), both of which do not include active pile driving (Table 1). Each pile was driven with both a vibratory and impact hammer, and the fish kill events were not exclusively associated with construction periods employing either of these hammer types.

Two non-ESA listed species of fish were observed during the fish kill events at CVOW-C; Atlantic croaker (*Micropogonias undulatus*) was the most common species observed and spot (*Leiostomus xanthurus*) were observed in fewer numbers. The quantity of observed fish varied per observation with an average of 430 fish per observation (Table 1). Approximately 75% of the observations were made within 1 km of the pile being monitored during pile driving activities; 25% were made greater than 1 km from the pile. Drifting of fish and delayed observation may have affected the timing and the distance from the pile where the observation was made. This may have led to some overcounting of fish and inaccurate assessment of the timing of events and thus hindered the ability to link the event with any causal factors.

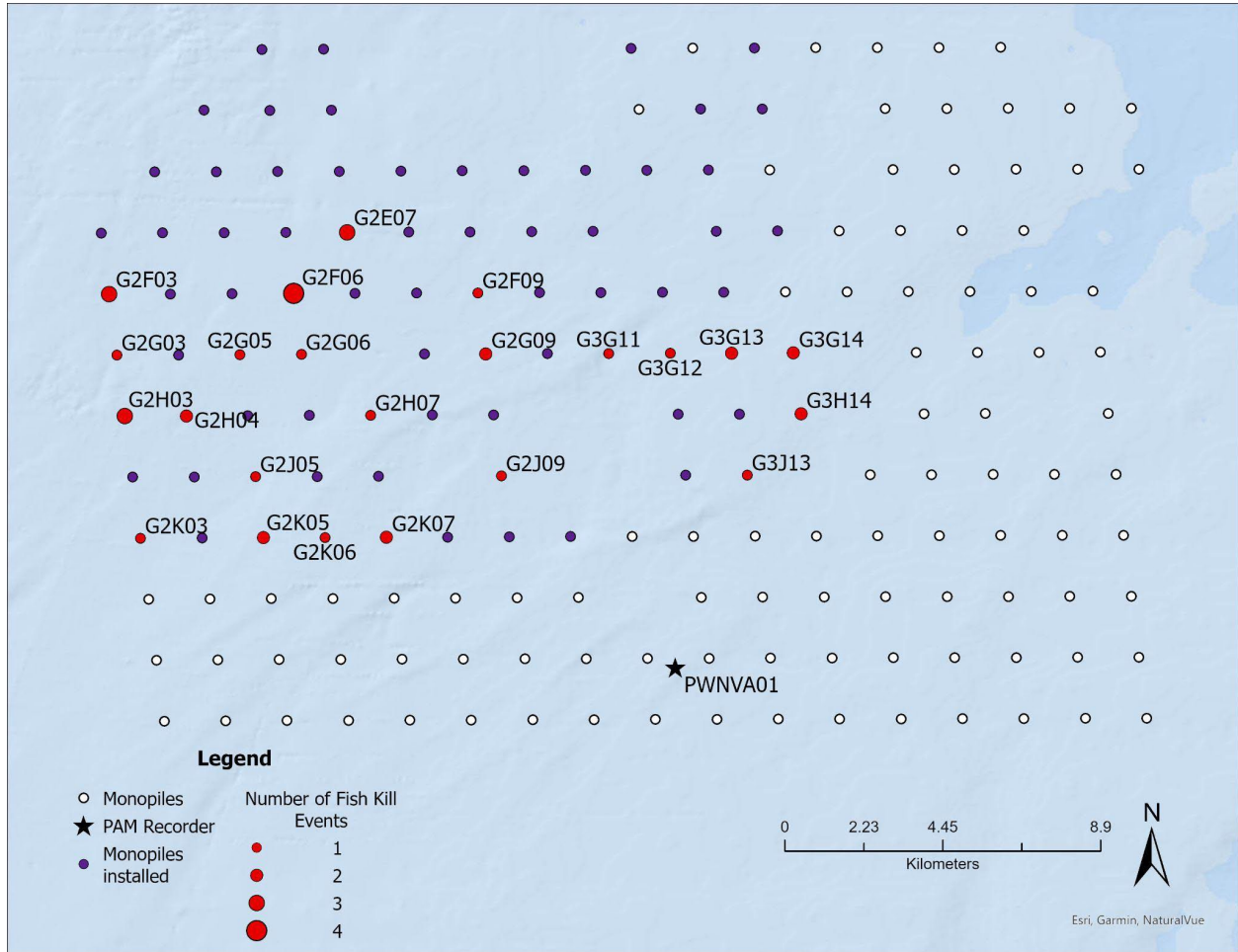


Figure 4. Map of planned monopile installation and PAM recording location within CVOW-C. Monopile locations are indicated by dots. Blue dots indicate monopiles that were installed during this monitoring period and did not have a fish kill observation; red dots indicate monopiles that were installed and the number of fish kill events observed; and white dots indicate planned monopiles that were not installed during this monitoring period. Monopile labels indicate the name of the monopiles where fish kills were observed. Note that one of the 39 events had no monopile recorded, so only 23 of the 24 pile locations where fish kill events occurred are shown on the map.

Table 1. Fish kill statistics associated with each stage of construction. Table courtesy of BOEM. Mean distance (m) from the piling that the observation was made (=sum of distances for each observation divided by the number of observations); Mean number of fish observed (=total number of fish observed divided by the number of observations for the construction activity type); Total number of fish per construction activity type; Number of observations per activity type; % of the total number of fish (N=18,102) that were observed during a given type of construction activity; and % of the total number of observations (N=39) that occurred during a given type of construction activity type.

Construction Activity Type	Mean Distance from Pile (m)	Mean # of Fish Observed	Total # of Fish	# of Obs.	% of Obs. Fish	% of Obs.
No Construction	2,420	690	3,450	5	19%	13%
Pre-Install	487	716	10,740	15	59%	38%
Vibratory Piling	99	194	970	5	5%	13%
Switch (i.e., Post Vibratory but Pre Impact	606	163	1,792	11	10%	28%
Impact Piling	3,038	383	1,150	3	6%	8%
Total			18,102	39		

Ten observations occurred >1 km from a pile location. Of these, 60% (6 observations) had pile driving occurring the day immediately prior, four of which reported fish kill observations. Of the other four observations, three occurred two days after pile driving and the other occurred three days after pile driving, and the one that was observed two days after piling activity was the earliest observation reported, which may relate to its delayed observation.

Fish may have drifted from the location where they died. All but two of the far-field (>1 km) observations of dead fish relative to the pile-driving location were observed only after pile driving days on which near-field fish kills were observed (Table 2, Figure 5). For example, pile driving at piles G2F07, G2E07, G2F06, and G2F03, occurred on June 22, June 23, June 25, and June 26, respectively. Conversely, no observations at >1 km from a pile location were made after a long pause in pile driving. This may indicate that the fish observed >1 km away from piling had

drifted from a previous event and were either unseen previously (i.e. an unnoticed event), or observations were being double counted, rather than a separate event occurring at such a large distance from construction activity. Information about current direction and speed is recorded during piling and on meteorological buoys and could be used for further study into drift patterns of these distant fish.

Table 2: Potential fish “drift”. Consecutive dates on which piles G2F07 (June 22), G2E07 (June 23), G2F06 (June 25), and G2F03 (June 26) were driven with both vibratory and impact pile driving at each pile; whether or not a fish kill was observed; and the far-field (>1 km) and near-field (≥ 1 km) distances at which dead fish were observed. This subset of pile driving dates was chosen to illustrate that far-field fish kills were only observed after pile driving days on which near-field fish kills were observed, which suggests that fish may have “drifted” to these far-field locations.^a For June 24, a fish kill was observed despite no pile driving activity on that date; therefore, there is no distance from pile recorded.

Date	Pile Driving Occurred	Fish Kill Observation	Far-Field Fish Kill Observation Distances from Pile Driving	Near-Field Fish Kill Observation Distances from Pile Driving
22-June-2024	Yes	No		
23-June-2024	Yes	Yes		150 m, 80 m, 60m
24-June-2024 ^a	No	Yes		
25-June-2024	Yes	Yes	3463 m, 2900 m	125 m, 1 m
26-June-2024	Yes	Yes	3000 m	350 m, 160 m

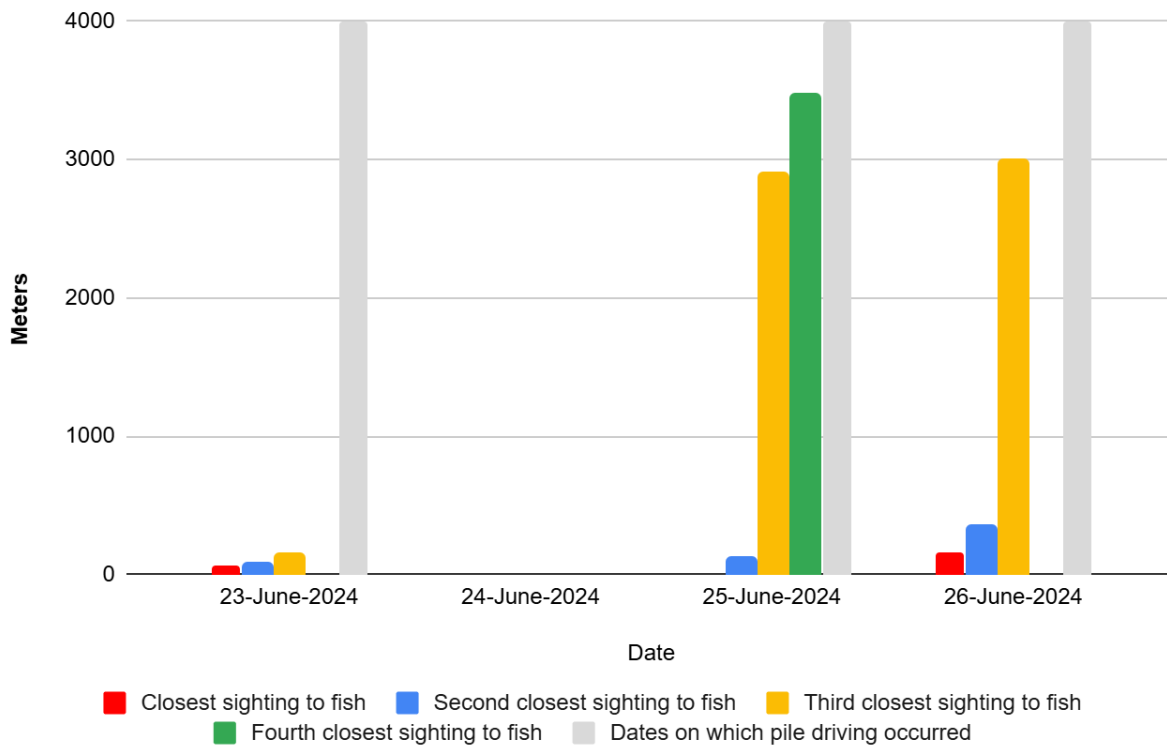


Figure 5. Potential fish “drift”. Distance (m) between pile driving location and fish kills on four consecutive dates. These dates correspond to the piles depicted in Table 2: G2E07 (June 23), G2F06 (June 25), and G2F03 (June 26) which were driven with both vibratory and impact hammers at each pile; This subset of pile driving dates was chosen to illustrate that far-field fish kills were only observed after pile driving days on which near-field fish kills were observed, which suggests that fish may have “drifted” to these far-field locations. Note that on June 24, a fish kill was observed despite no pile driving activity on that date; therefore, there is no distance from pile recorded.

4.2 Ecology of Affected Species

Both Atlantic croaker and spot are members of the Sciaenidae family commonly found in the Mid-Atlantic region and both share similar life histories. They are both considered bottom-dwellers and feed on benthic prey in sandy and muddy substrates (Odell et al., 2017). Atlantic croaker and spot both have a broad spatial distribution that extends from Massachusetts to Mexico (Robins et al. 1986). Both species also live in different habitats in different phases of life; specifically, eggs migrate inshore to settle in estuaries as larvae, juveniles remain in the inshore benthic zone, and adults migrate offshore to spawn (Odell et al., 2017). Atlantic croaker are fall/winter pelagic spawners on the continental shelf in depths from 7 to 31 m (SC SWAP, 2015), while spot tend to spawn in the winter further offshore and in deeper waters than Atlantic croaker, with depths up to 82 m (Odell et al., 2017). Once of spawning age, spot remain offshore the majority of their adult life, while croaker tend to be found in different habitats both inshore and offshore (Petrik et al., 1999). Both Atlantic croaker and spot display high site fidelity, and thus

may be more vulnerable to stressors since they are less likely to depart the area of stress (Jarriel et al. 2024). Atlantic croaker and spot both have closed swim bladders (physoclistous), making them more vulnerable to severe injuries from impact pile driving sounds compared to fishes with no swim bladder or open swim bladders (Halvorsen et al. 2012; Casper et al. 2013). Atlantic croaker are targeted by commercial and recreational fisheries. In 2023, approximately 2.3 million pounds of Atlantic croaker were landed, 78% of which were by recreational fisheries (ASMFC 2025). The majority of recreational harvest occurs in Virginia whereas the majority of commercial landings occur in North Carolina (ASMFC 2025).

4.3 Information from Opportunistic Necropsies

Reviewing the details surrounding the fish kill events in combination with the statistics of the individuals, such as the proportion of the impacted individuals belonging to a given species or age class, can be very helpful in determining a cause of the event. For instance, a fish kill that occurs slowly over multiple days is likely to be caused by depleting oxygen while all fish dying abruptly may be linked to a suddenly toxic environment. If one species is impacted and not others, the cause may be an infectious agent (Meyer and Barclay 1990, La and Cooke 2011). Size of fish is also an important factor, as depressed oxygen levels will likely not include smaller fish because smaller fish require less oxygen, whereas toxin-related kills will include fish of all sizes (Kane 1999). It is important to know if the impacted fish were in generally good health prior to the fish kill event or if any preexisting conditions may have influenced the fish kill (Wobeser 1996).

Samples of a small number (N=35) of individual fish were collected and sent for opportunistic necropsy to better understand the CVOW-C fish kill events. Notably, there was no requirement or established protocol to collect, necropsy, or otherwise document the fish kill events included in the Terms and Conditions of the CVOW-C COP. However, the decision was made to collect and analyze these samples following receipt of multiple reports at the CVOW-C project and discussion between BOEM, NMFS, and Dominion Energy. At the time of the initial necropsy, there was no guidance provided by NMFS or BOEM on how to collect, handle, transport, or store samples, and it is unknown if any guidance was provided by other entities. Subsequently, guidance was provided on sample size to be collected for necropsy (by NMFS staff) and on the method of sample preservation (by BOEM staff).

An initial opportunistic necropsy (Dominion 2024a) was conducted at Virginia Institute of Marine Science (VIMS) using seven specimens that had been frozen for preservation and subsequently thawed for necropsy. Using macroscopic observations only, this necropsy identified some injuries consistent with acoustic trauma (e.g., ocular hematomas, damaged eyes, deflated swim bladders); however, this necropsy also found other injuries (e.g., broken bones, bruised muscles) that are consistent with multiple causal factors including, but not limited to: acoustic trauma, exposure to gas supersaturation, and collection including interaction with capture gear, handling, packing and preservation methods such as freezing and thawing (Table 3). Because the

packing process and preservation method of freezing followed by thawing may cause some of the injuries observed in the necropsy, the results must be interpreted with caution. In addition, the small sample size (n=7 fish) was only examined grossly with no histological samples taken or microscopic examination. This limits the ability to determine the likely cause of death. The VIMS necropsy concluded that the injuries observed were consistent with exposure to pile driving operations but that they were also consistent with other potential causal factors.

A second opportunistic necropsy occurred at North Carolina State University (NCSU) College of Veterinary Medicine (Dominion 2024b) from a second batch of 28 specimens (25 Atlantic croaker and 3 spot). These samples were preserved on ice but not frozen. The necropsy findings indicated that the fish were, “in appropriate body condition with adequate muscling and digesta present in the gastrointestinal tract.” Similar injuries were identified by the NCSU and VIMS necropsies (Table 3). The NCSU necropsy identified multiple rib and vertebral fractures with coordinating hemorrhages as well as gas accumulation in the gill vasculature. The necropsy report made note of acute trauma leading to hemorrhage and fractures, while the swim bladder deflation and gas accumulation is consistent with unbalanced gas saturation in the blood which can occur with rapid ascent in the water column and/or being caught in waters supersaturated with dissolved gasses (*sensu* McLeod 1978). The report indicates some individuals had head and spinal injuries but it is unclear whether these were related to the fish kills event or a secondary effect that occurred postmortem. The NCSU necropsy concluded that “overt skeletal trauma is likely the more specific lesion, with gas bubbles speculatively accumulating secondary to ascent” but could not assign definitive causes to these injuries.

Stomach content analysis was also conducted during the NCSU necropsy for specimens that had intact stomachs. Five of the 17 analyzed (two from the first necropsy, 15 from the second) had contents consistent with Atlantic Croaker diet, the rest had either gastric liquid or were considered "empty". The analyst noted degradation of the tissues due to multiple freeze/thaw cycles. As the digestive process can continue post mortem even when stored on ice, the analyst recommended following procedures developed by VIMS for gut content analysis (Bonzek et al. 2022) should these be requested again.

Taken together, the VIMS and NCSU necropsy findings indicate that specimens may have experienced acute trauma prior to or during rapid ascent in water supersaturated with dissolved oxygen (Table 3). However, neither report was able to determine a definitive cause due to the limited information available.

Table 3: Summary of injuries observed in necropsies and potential causes.

Injury Observed in Necropsy	Potential Causes	Citation that Provides Information on the Potential Cause
Skeletal fractures; Bruised muscles	Acoustic Trauma; Collection, handling, preservation method; Bubble curtain pressure; Collision; Predation	NASEM 2011; Cox et al. 2023
Ocular hematomas; Damaged eyes, Deflated swim bladders	Acoustic Trauma; Gas supersaturation; Collection, handling, or preservation method (e.g., freezing/thawing)	Bouck 1980, Machova et al. 2017
Gas accumulation in the gill vasculature	Rapid ascent in the water column; Supersaturated waters such as those from bubble curtains	McLeod 1978

5. WATER TEMPERATURE DATA

Water temperature data were available from an unrelated study that was being conducted by The Nature Conservancy at the nearby CVOW-Pilot project during the time of the fish kills (Brendan Runde, pers. comm.). CVOW-Pilot is located on the western edge of CVOW-C on a separate but adjacent wind lease. Water temperature loggers were deployed at CVOW-Pilot approximately 1 m above the seafloor (36° 53.921'N, 75° 29.398'W). Deployment of the loggers began February 4, 2024 with the initial download occurring June 4, 2024 and a second download October 6, 2024. Water temperature was recorded hourly during this time period. Evaluation of these data indicate that there were no anomalous temperatures during the time of the fish kills in the vicinity of CVOW-Pilot where the temperature loggers were located. Means and standard deviations are as follows: May: 12.5 ± 1.2 °C; June: 12.2 ± 0.8 °C; July: 11.4 ± 0.6 °C; August: 10.9 ± 0.6 °C. (Brendan Runde, pers. comm.).

6. PASSIVE ACOUSTIC MONITORING (PAM) DATA

Passive acoustic monitoring (PAM) within CVOW-C was conducted by the NOAA Northeast Fisheries Science Center as part of the BOEM Partnership for an Offshore Wind Energy Regional Observation Network (POWERON) Initiative. To date, conditions of all COP approvals issued by BOEM require PAM to facilitate assessment of noise associated with pile driving and assess potential impacts to marine animals and the soundscape. The collection of PAM data coincided with the fish kill events.

6.1 Collection of PAM Data

A single bottom-mounted acoustic recorder (Soundtrap 600, noise is less than sea-state 0 at 100 Hz–2 kHz and <36 dB re 1 μ Pa above 2 kHz; system end-to-end calibration: 175.8 dB re 1 V/ μ Pa; Ocean Instruments, Inc.) programmed to record continuously at a 48 kHz sampling rate was deployed at 23 m depth in the southern region of the wind energy lease at a location pre-determined in coordination with Dominion Energy (36° 56.183'N, 75° 20.181'W; Figure 1). The recorder was maintained year-round though this memo focuses on the sampling period that overlapped with construction activities from April 18, 2024 - September 10, 2024. The distance between the PAM recorder and the monopiles that were installed during the sampling period ranged from approximately 4.4–19.7 km.

6.2 Analysis of PAM Data

Acoustic data were quality controlled to ensure there were no data gaps or compromised data. The soundscape was summarized into daily Hybrid millidecade spectra (HMD) using PyPAM-based processing (PBP), an open-source python tool to calculate sound metrics from passive acoustic data. PBP output includes the daily HMD spectra and an image of the daily HMD referred to as a long-term spectrogram average (LTSA).

Acoustic data were integrated with data from construction and PSO reports to investigate the potential interaction between the soundscape, construction activity, and fish kill events. Information about bubble curtain activity was extracted from the Double Big Bubble Curtain Performance Reports submitted on behalf of Dominion Energy. Each report detailed the weather conditions, hose deployment report, and compressor log of each monopile installed. Impact and vibratory pile driving information was extracted from the construction activity reports provided by Dominion Energy to BOEM. All data set integration and statistical analysis was completed using R studio (version 4.3.2).

Marine soundscapes can contain vast amounts of anthropogenic, biological, and environmental information. In an attempt to attribute patterns in observed sound levels to anthropogenic noise and construction activities specifically, sound level data were summarized using the 125 Hz octave level band. This frequency band contains the peak frequency of impact pile driving sounds and overlaps with known bubble curtain and vessel sounds, while excluding the most common fish sounds observed (Betke 2008; Van Parijs et al., 2023; Beelen et al., 2025). To understand the patterns in sound level during various construction activities, hourly observed sound pressure levels (SPLs) were compared across the status of construction activity. These statuses included no construction, DBBC only, impact pile driving only, and vibratory pile driving only, where no construction means the DBBC is off and no impact or vibratory pile driving was occurring. The DBBC only status included data during all aspects of DBBC operation including flushing, pressure testing, and full pressure operation but excluded data when pile driving was

occurring. Similarly, it is important to note that the DBBC is intended to be operational 30 minutes before pile driving begins during all impact and vibratory pile driving periods. These grouped SPLs by construction activity were found to be non-normally distributed under the Shapiro-Wilk test and non-homogeneous under the Levene test. Given this, statistical difference between the groups was evaluated using a Kruskal-Wallis nonparametric test and post-hoc Dunn test with the Bonferroni correction. To explore patterns in sound level when a fish kill was or was not observed, daily SPL time series were visualized for four representative days that monopiles were installed at a range of distances away from the PAM recorder.

Because the fish kills were documented during construction, additional analysis of the passive acoustic data focused on calculating overall sound levels and identifying fish sounds observed. The LTSAs were visually scanned for the presence of fish chorusing, identified by repetitive high-intensity sounds that are consistent in frequency and diel pattern and typically associated with spawning. When fish chorusing or other sounds of interest were observed, the full audio files were visually and aurally inspected in Raven Pro (K. Lisa Yang Center for Biodiversity Conservation, Cornell Lab of Ornithology) to identify and describe the sound. Sounds of interest included low-frequency sounds that align with typical characteristics of fish or anthropogenic sounds. Unknown fish sounds were compared to documented fish sounds in the literature and FishSounds database in an attempt to identify the specific source (Looby et al., 2025).

6.3 Results of PAM Data Analysis and Interpretation

Comparison of observed 125 Hz octave level SPLs revealed a significant difference in median SPLs among construction activity statuses (Kruskal Wallis: $\chi^2 = 172.65$, $df = 3$, $p < 0.001$). Visualization of the observed SPLs by construction activity statuses suggest that hours during DBBC only, impact pile driving, and vibratory pile driving activity all had significantly higher SPLs than hours when no construction activities were occurring ($p < 0.05$, Figure 6 boxplot).

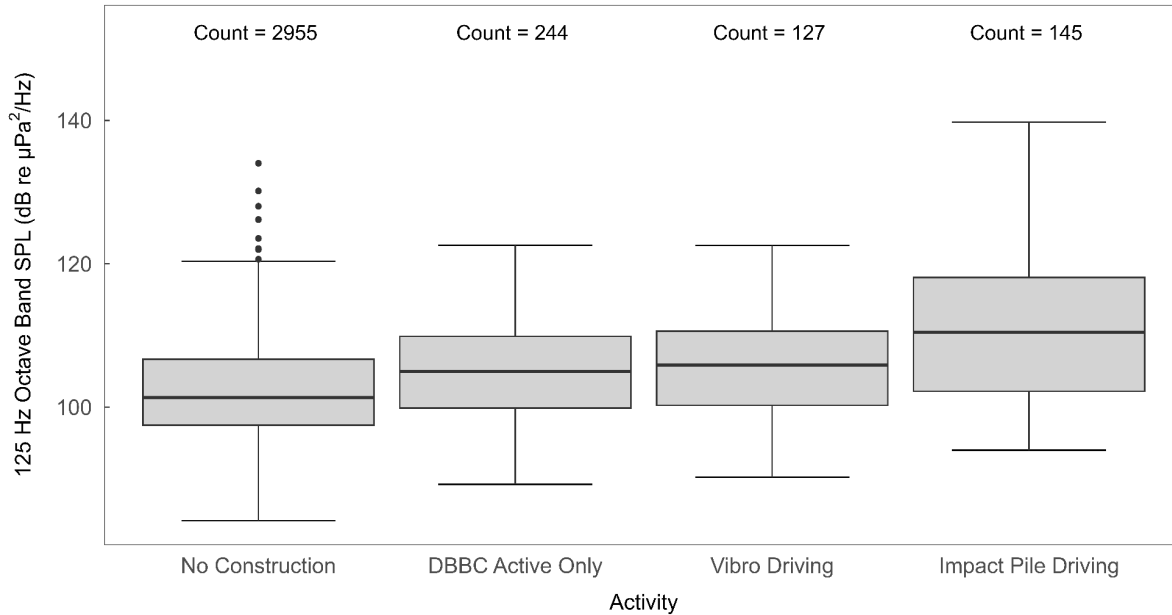


Figure 6. Summary of hourly observed 125 Hz octave level SPL during various construction activities (DBBC Active Only, impact pile driving, vibratory (vibro) pile driving) and when no construction activity was occurring. Note that the bubble curtain is on during the impact and vibratory pile driving. Solid black line indicated median, box edges represent 0.25 and 0.75 quantiles, outliers represented as points, counts indicate the number of hours summarized for each box plot.

Inspection of the daily time series from four representative days that monopiles were installed revealed variable temporal patterns across the construction period (Figure 7 timeseries). Notable observations included clear increases in observed SPLs while impact pile driving was occurring at monopiles G3H13 and G3J13 on August 23rd and G2F09 on August 6th. Inspection of the PAM audio data during these periods confirmed that impact pile driving was clearly visible and audible in the recording, even when conducted over 11 km away from the recorder. Fish kills were observed within 100 m of these monopiles while the DBBC was active but no impact or vibratory pile driving was occurring. Additionally, there is no apparent increase in sound level immediately prior to the fish kill event. Daily time series when monopiles G2K09, G3H13, and G2G10 were installed were included for comparison between days when no fish kills were observed. Across all daily time series, SPLs were variable during the active DBBC and vibratory pile driving periods with no clear patterns or discernible peaks in activity.



Figure 7. Daily time series of observed 125 Hz Octave Band SPLs visualized with shading indicating the associated construction activity that was occurring during specific monopiles installations (Note that the first two time series contain multiple piles). Note that the DBBC was also on while impact pile driving and vibratory pile driving were occurring.

While these daily examples are helpful for evaluating consistent patterns, multiple, notable limitations remain. Most relevant is that the 125 Hz octave level was chosen as the best available proxy to isolate anthropogenic noise associated with construction; however, any inferences made are correlative and cannot be directly attributed to construction activity. While some impact pile driving was clearly identifiable in the audio at distant monopiles, the recorder was far away from the majority of piles that were installed during this phase of construction, increasing the difficulty to attribute sound sources at certain sites. To reduce the risk of double counting fish kill observations due to repetitive sightings after fish at the surface drifted with currents, integration of PAM and fish kill observations were limited to only the fish kills observed within 100 m of a monopile. Of these observations, a majority² of the fish kills occurred while the DBBC was on. While bubble curtain noise can be clearly observed in soundscape data when recording close enough to the monopile, inspection of the audio data revealed increases in ambient sound levels

² This can be conservatively estimated to be 69% of observations using the PSO reports that indicate whether or not the DBBC was turned on. Not all PSO reports indicated whether the DBBC was turned on. This number could be higher if the order of operations was followed correctly for each of the piles, and the PSO reports accurately relayed the step of construction during which the fish were observed.

concurrent with DBBC onset activity, but there was no confidently discernible bubble curtain noise present. Moreover, bubble curtains produce very broadband noise that is most intense under 500 Hz, but does extend up to 20 kHz. As such, the 125 Hz octave level recording multiple kilometers away from the monopile is likely not the ideal configuration for monitoring sound levels associated with bubble curtain activity. Lastly, the timing of a fish kill is based on opportunistic observations of killed fish as documented in PSO reports and not the actual observed mortality event. An unknown amount of time passed between the mortality event and when the fish were observed at the surface resulting in observation error. This was accounted for in the PAM analysis by only investigating fish kill events that were observed within 100 m from a monopile.

Broader analysis of the soundscape revealed the presence of fish chorusing throughout the monitoring period. Visual inspection of the LTSAs suggested that fish chorusing began on 05/09/2024 and continued daily through 09/06/2024 with minimal interruptions. The diel pattern of chorus activity was crepuscular, beginning around astronomical twilight and ending a few hours before sunrise. Specifically, chorusing typically started around 19:45 local time and lasted throughout the night until approximately 04:00, for a total duration of about eight hours. The fish chorus had a large frequency range, with a minimum frequency of approximately 0.3 kHz and a maximum frequency that varied between 4–5 kHz.

A current limitation of PAM for fish is a lack of information that pairs observed fish sounds with their species identity (Looby et al., 2023) and their specific location. As a result, we are not currently able to identify the fish species that are chorusing or localize aggregations in the area. Although it cannot be determined whether chorusing fish were located within or outside the wind project, it can be stated that they were located in the vicinity of CVOW-C within the listening range of the hydrophone. The temporal and frequency characteristics of the chorus are similar to that of other documented sciaenid species, including silver perch (Mueller et al., 2020, Monczak et al., 2019) and Atlantic croaker (Mueller et al., 2020), but it is unlikely that the observed chorus was Atlantic croaker. Fish chorusing is typically associated with spawning activity and the chorus was observed during spring/summer, while Atlantic croaker spawn in fall/winter. However, it should be noted that fish chorusing patterns appeared to be independent of anthropogenic disruption, remaining consistent throughout the period of analysis, despite the persistent presence of anthropogenic noise associated with construction activity and the observed fish kills of Atlantic croaker and spot (Figure 8 chorus/construction timeseries).

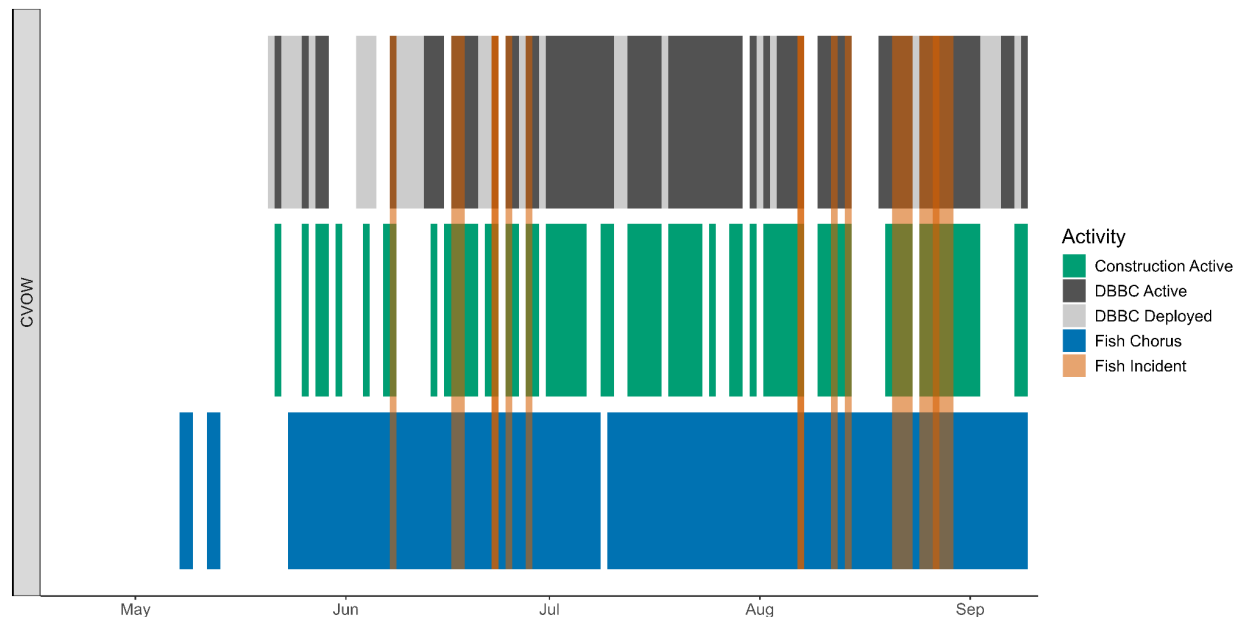


Figure 8. Observations of fish kills observed less than 100 m from a monopile overlaid on the record of DBBC and construction activity (i.e., either vibratory pile driving or impact pile driving and DBBC on) as well as observations of fish chorusing during the passive acoustic monitoring period. Fish kills appear to have typically occurred during construction activity and when the DBBC was active. Fish chorusing continued throughout the monitoring period, independent of the fish kill events.

7. FACTORS ASSOCIATED WITH FISH INJURY AND MORTALITY THAT HAVE BEEN REPORTED IN THE LITERATURE FROM OTHER FISH KILL EVENTS

Based on an assessment of the peer-reviewed literature, there are no documented incidences of large-scale fish mortality associated specifically with offshore wind energy construction elsewhere in the world, aside from the ones reported here. However, there is ample evidence in the literature of fish injury and mortality due to exposure to similar stressors arising from different anthropogenic activities that are not related to offshore wind development (Table 3).

7.1 Pile Driving Noise

Pile-driving generates both sound pressure, particle motion, and substrate vibration. Many marine fish species are sensitive to anthropogenic noise (Popper and Hastings 2009; Popper et al. 2022), including Atlantic croaker (*Micropogonias undulatus*), (Horodysky et al. 2008) the primary species identified in the CVOW-C event. Anthropogenic noise can be associated with mortality as well as many sublethal effects including physical injury (i.e., barotrauma), physiological and stress responses, altered behavior, and communication masking (Popper and Hastings 2009; NASEM 2011; Cox et al. 2018, Horodysky et al. 2022, Fuqiang et al. 2023, and Kim et al. 2025). Studies

associated with coastal impact pile driving have found that fish species with closed swim bladders (physoclistous), like Atlantic croaker, spot, and white hake, show higher total and more severe injuries compared to fishes with no swim bladder or open swim bladders (physostomous) (Halvorsen et al. 2012; Casper et al. 2013). Impact pile driving and other impulsive sources have the potential to injure or kill fish by causing swim bladder resonance that can damage the organ itself as well as surrounding tissues and organs. A single field experiment related to offshore wind farm construction reported in the grey literature evaluated the effect of pile driving on Atlantic cod (*Gadus morhua*) using submerged, netted cages placed along a distance gradient each containing 9-12 individuals (De Backer et al. 2017). Necropsied individuals of *G. morhua* showed evidence of ruptured swim bladders and internal bleeding with an increasing proportion of affected individuals closer to the source (De Backer et al. 2017). Impact pile driving specifically is known to be injurious to fish species in shallow waters (<100 m, Richardson et al. 1995; CalTrans 2020) particularly in the absence of noise mitigation methods, such as bubble curtains (CalTrans 2020; Popper et al. 2019a). Notably, dead fish were observed at CVOW-C prior to pile driving.

7.2 Bubble Curtains and Gas Bubble Trauma

Noise mitigation via a noise abatement system (NAS) is included in the Terms and Conditions of the COP for individual offshore wind projects. Specific requirements are also included in MMPA ITAs and ESA Biological Opinion's issued by NMFS. A variety of NAS configurations are available, and a project can use one or multiple depending on the project specific requirements. Examples include an array of resonators, a noise mitigation screen, damping systems connected to the hammer, and/or bubble curtains.

Bubble curtains are commonly used as NAS in offshore wind projects overseas (e.g., Dähne et al. 2017; Bellmann et al. 2022) and in domestic nearshore construction (e.g., bridge construction, CalTrans 2020). A bubble curtain is created by a hose with holes that is deployed on the seafloor and has pressurized air delivered through it at a certain flow rate. This pressurized air creates bubbles rising to the surface in a "curtain" of sufficient density to attenuate sound. This hose can be laid in a variety of configurations, but is typically arranged in a circle or oval for NAS during offshore wind pile driving. Bubble curtains are used for many purposes in addition to NAS, which include: the prevention of saltwater intrusion (e.g. Abraham and Burgh 1964, Talebi et al. 2022); prevention of biofouling (e.g. Scardino et al. 2014); prevention of freezing of harbor/fjord water (e.g. Ince 1964); promotion of non-toxic algal growth (e.g. McClimans et al. 2010); as oil spill controls (e.g. Feng and Zhang 2023); for experimental sediment transport control (e.g. Covarrubias-Contreras et al. 2025); and as fish deterrence systems (e.g. Zielinski et al. 2014, Zielinski et al. 2016, Hollarsmith et al. 2025).

A potential mechanism of fish injury or mortality from interaction with a bubble curtain is gas bubble trauma (GBT), or a build-up of high levels of gas inside of a fish's body when a fish encounters water with high levels of dissolved gases (Pleizier and Brauner 2024; Pleizier et al.

2020). This may arise in situations where water is aerated under conditions of high flow and pressure leading to high concentrations of bubbles in the water, as is the case with bubble curtains. The uptake of bubbles across fish gills can cause embolisms in the circulatory system and numerous tissues, potentially resulting in lethal and sublethal effects; these include but are not limited to effects on biological processes (e.g., blood gas regulation, nitrogenous waste excretion) and damage to bodily structure, organs, and tissues (e.g. eyes) (McLeod 1978; Pleizier and Brauner 2024; Pleizier et al. 2020). Water can become supersaturated with dissolved gasses from both natural and anthropogenic causes, for instance the base of a waterfall or the spillover from hydroelectric dams, or due to heavy photosynthetic activity, each of which has led to fish mortality events (Pleizer and Brauner 2024; Kusnierz et al 2023; Yuan et al 2022). There is currently no published literature that associates fish mortality with bubble curtains deployed for the purpose of attenuating pile driving noise and GBT. There are also no known monitoring requirements to ascertain fish interactions associated with bubble curtain deployments.

Anthropogenic activities generate multiple simultaneous stressors. Many of the causes of GBT and supersaturation of dissolved gases are anthropogenic causes in which hydrodynamic effects are also a contributing factor to injuries in fish; therefore, it is possible that the hydrodynamic effects of the bubble curtains may also contribute to injuries. Multiple factors arising from hydraulic stressors, including shear stress, pressure changes, acceleration/deceleration, turbulence, aeration, cavitation, and collision/strikes, have the potential to cause injury and death. Previous research examining hydraulic stressors and GBT has catalogued many of the same injuries seen in the fish during the events at CVOW-C, including ruptured swim bladders, gas bubbles, eye loss/injury, spinal injury, and decapitation (Cox et al. 2023, Turnpenny et al. 2000, Long et al. 2019, Fivelstad 2020, Pleizier et al. 2019). Some of the fish at CVOW-C were moribund which is also consistent with previous research of hydraulic stressors which found effects on fish to include disorientation, rotation, and predation (Cox et al. 2023, Turnpenny et al. 2000, Long et al. 2019, Fivelstad 2020, Pleizier et al. 2019).

The high velocity flows of hydraulic systems are associated with turbulence and aeration, and air entrained for extended periods can lead to supersaturation (Cox et al 2023)³. The fluctuating velocity components of these turbulent flows create shear stress, and the vortical motion can entrap fish. These flows can also include pressure changes, including changes in depth or acceleration, and significant pressure changes occurring faster than a fish can accommodate have the potential to harm fish, which means that physoclistous fish may experience more injuries than physostome fish for similar levels of effects⁴. While accelerating, one end of a fish may experience a higher velocity than the other, stretching the fish, though the impact and injuries are affected by the direction of flow relative to the angle of the fish entering the flow (Cox et al 2023)⁵. Additionally, fish size and shape has much to do with the exposure, for example the head shape has been

³ At CVOW-C, the necropsies noted gas accumulation and GBT.

⁴ At CVOW-C, the necropsies noted ruptured and damaged swim bladders.

⁵ At CVOW-C, the necropsies noted vertebral fractures and decapitated heads (internally and externally).

theorized to be a factor in better tolerating pressure changes causing eye injuries, and body length increases the potential for collision/strike (Cox et al 2023)⁶. While injuries from collision/strike tend to be external or major/fatal, injuries resulting from pressure changes are observed internally. Turbulence or jets can damage scales or force gills open, and cavitation can cause injuries to the eyes, operculum, and internal organs (Cox et al 2023) as well as make it difficult to obtain oxygen when surrounded by gas and cavity bubbles (Long et al 2019).⁷ The inertia from tumbling in turbulent flows may lead to vestibular or neurological injuries (Long et al 2019).⁸

Many of the impacts tested in previous studies were in relation to fish transport such as a jet fish pump involving horizontal acceleration or entrainment in turbulence of a spillway, and the impacts of a bubble curtain were not studied (Cox et al. 2023, Turnpenny et al. 2000, Long et al. 2019, Fivelstad 2020, Pleizier et al. 2019). However, the effects of aeration, turbulence, shear stress, cavitation, and pressure changes should be explored as translatable to effects from the stressors of a bubble curtain.

7.3 Other Sources of Mortality

Several other factors may cause fish injury or mortality, including: sudden alterations in water chemistry such as temperature⁹, dissolved oxygen, salinity, nutrients, and pH; pollution from agricultural fertilizers, industrial chemical discharges, or vessel discharges; viral, bacterial or fungal disease, including biotoxins associated with algal blooms; direct physical trauma from ship or propeller strikes; or discarded bycatch from fishing vessels (Bourdelaïs et al. 2002, Gutreuter et al. 2023, Kane et al. 1999, Koehn 2022, Meyer and Barclay 1990; VA DEQ 2002).

⁶ At CVOW-C, the observations noted largely one species of fish, the necropsies indicated eye injuries, and the individuals collected randomly were roughly of the same size class, though an assessment of individual sizes was not conducted specifically.

⁷ At CVOW-C, damage was seen to each of these areas during necropsy, and moribund fish were seen gulping the air at the surface.

⁸ At CVOW-C, moribund fish were seen swimming erratically and/or in circles.

⁹ Water temperature data recorded near CVOW-C indicated no anomalous temperatures at the time of the fish kills.

8. CURRENT PROTOCOLS FOR FISH KILL EVENTS

Lessees are required to report incidences of non-ESA listed fish mortality as part of the Terms and Conditions the COP. Notably, these protocols only require documenting that the event occurred and reporting to BOEM in a timely manner. Specifically, when ≥ 10 deceased individuals of non-ESA listed fish are detected within the established shutdown or monitoring zones, the lessee must report the occurrence to BOEM as soon as practicable (taking into account crew and vessel safety), but no later than 24 hours after the sighting. The Terms and Conditions of the COP for CVOW-C only required reporting fish kill events to BOEM and BSEE, but the requirements of some project COPs require Lessees to include modifications that will be made to reduce the risk of additional fish kills in the project area when reporting a fish kill event. Some recommended protocols are available that outline how to accurately assess a large-scale fish kill event and provide the best-quality samples for study during a subsequent investigation (e.g. Kane et al. 1999, Meyer and Barclay 1990, and VA DEQ 2002).

Observations made by PSOs are limited by the spatial and temporal coverage of the PSO vessels. PSOs are located on the installation vessel and any dedicated PSO vessels, which are generally located at the perimeter of the monitoring and shutdown zones. The monitoring and shutdown zones vary across projects given project-specific conditions and requirements. PSO requirements and associated mitigation requirements are established through MMPA authorization and ESA consultation processes in cooperation with BOEM and/or the developer as appropriate. Project-specific details about PSOs are outlined in the Pile Driving Monitoring Plans, Protected Species Observer Plan and Terms and Conditions for BOEM COP approval as well as MMPA ITAs and ESA Biological Opinions. For CVOW-C monopile foundation installation, at least two visual PSOs were stationed on the pile-driving vessel and at least two visual PSOs were required to be stationed on a secondary, PSO-dedicated vessel, located 3 km from the pile being driven. In summer 2024, two dedicated PSO vessels worked concurrently at the CVOW-C foundation installation sites.

The number of dead non-ESA listed fish reported are estimated based on visual position, and therefore may be biased in unknown direction and magnitude. The parameters that trigger required reporting vary across projects. At CVOW-C, the Conditions of BOEM COP Approval require the Lessee to report the event to BOEM or BSEE following the reported occurrence of ≥ 10 deceased individuals of non-ESA listed fish, and BOEM or BSEE are to subsequently notify NOAA Fisheries Greater Atlantic Regional Office of the observations. The Lessee is responsible for confirming that the reporting was received, but no other actions are required. Upon receiving the report on the CVOW-C fish kills, BOEM requested Dominion Energy to opportunistically collect dead fish for necropsy, although no such action was required by the Conditions of COP Approval. This request and the subsequent coordination between Dominion and federal officials facilitated valuable information gathering that is summarized in this memo and may lead to increased understanding of the conditions surrounding the fish kill events.

9. DISCUSSION

Synthesis of Fish Kill Data, Necropsy Data, and PAM Data

This memo provides comprehensive documentation of opportunistic monitoring at CVOW-C in response to repeated, unexpected mortality events of non-ESA listed fish in spring/summer 2024. It is not possible to definitively attribute a causal mechanism for the mortality events because of the *ad hoc* nature of the sampling. Of the 19 fish kill observations that occurred within 100 m of a monopile, each occurred while the DBBC was deployed and active, either prior to pile driving activity, during the hammer switch/impact clearance activity, or during vibratory pile driving. The necropsy reports provide evidence of gas trauma that could be consistent with damage caused by the operation of a bubble curtain (in the case of CVOW-C, a DBBC), although the quality of some samples were limited by the packing process and preservation method. Passive acoustic monitoring within the wind energy lease area suggests that low-frequency sound levels, associated with pile driving noise and of relevance to fish hearing (Popper et al., 2019b), were greater during periods of active construction compared to when there were no construction activities occurring. However, sound levels were greatest during impact pile driving activity, and there were no clear increases in sound level prior to the observation of fish kills. Taken together, this information suggests that the fish kill events reported here are unlikely to be associated with acoustic trauma from pile driving and more likely could be associated with gas bubble trauma or other interactions with the bubble curtain (in the case of CVOW-C, a DBBC), although this cannot be conclusively stated.

While this report provides only correlative summaries, there are a few limitations that are important to address. For example, observations of fish injury or mortality events are biased towards fish species that have a swim bladder and can be observed floating after injury or mortality. As such, if any fish lacking swim bladders, such as flatfishes, skates, and rays, were impacted by the construction activities they will stay on the seafloor and likely be missed by any visual observations at the surface (e.g., VA DEQ 2002). This bias may lead to underestimating morbidity and/or mortality resulting from construction and operation phases, and could limit or skew inferences drawn about possible or likely causes of the observed events.

Passive acoustic monitoring provides summaries of observed fluctuations in sound pressure that did not correlate with observed events at CVOW-C; however, it is important to note that while all fish species resolve particle motion components of sound (Popper et al., 2019b), only a subset of species with certain anatomical adaptations can also resolve sound pressure (reviewed in Horodysky et al. 2022). While sound pressure and particle motion correlate, it is possible that there are connections between acoustic-related trauma due to particle motion and the fish mortality events; however, no particle motion data were collected at CVOW-C. Moreover, due to the location of the recorder, it was not possible to describe the acoustic environment proximal to the

monopile during construction activities, affecting the ability to infer correlations between changes in the soundscape and specific construction activities. While passive acoustic monitoring for sound field verification is conducted around 750 m from the monopile being installed, these reports provide estimated source levels for impact and vibratory pile driving, but do not include any acoustic information related to the bubble curtain activity (BOEM 2023).

Lastly, these fish kill events were unexpected and monitored on an opportunistic or *ad hoc* basis through collaboration between NOAA Fisheries, BOEM, Dominion Energy, and academic institutions. As such, there are uncertainties regarding the fish kill observation reports (e.g., risk of duplicate observations after fish drifted at the surface, VA DEQ 2002) and the conclusions drawn from necropsy reports (e.g., whether tissue condition was a result of in-situ trauma or improper storage).

10. REVOLUTION WIND FISH KILLS

Smaller fish kill events were also noted in 2024 at the Revolution Wind project. Revolution Wind¹⁰ is a 704 MW project in Southern New England located 15 miles from the coast of Rhode Island. This project plans to install 65 monopile turbines that are each capable of generating 11 MW of energy. In 2024, 52 of the planned 65 monopile foundations were installed within the Revolution Wind project area. Four observations were made by PSOs at Revolution Wind of dead fish during the summer of 2024. The main species reported was white hake (*Urophycis tenuis*). A total of 75 fish were estimated to be affected including 31 white hake on July 15 (initially reported as sea robins *Prionotus carolinus* but later corrected); 12 white hake on July 16; >20 white hake on July 20; and 12 white hake on July 21.

Similar to CVOW-C, when dead non-ESA listed fish are observed at Revolution Wind, the Terms and Conditions of BOEM COP approval only require reporting the occurrence to BOEM and BSEE; no other data collection is required. Revolution Wind also had a concentric circle DBBC configuration although the radii were smaller than those used at CVOW-C (two concentric circles of radii of 57 m and 103 m at Revolution Wind compared to 85 m and 123.6 m at CVOW-C). There were some notable differences between the CVOW-C and Revolution Wind fish kill events: 1) one dedicated PSO support vessel was present at Revolution Wind (compared to two support vessels at CVOW-C); 2) the monitoring zone in the summer was a circular area with a 2.3 km radius from the monopile being installed (compared with 3 km at CVOW-C); 3) Revolution Wind only utilized impact pile driving, not vibratory pile driving, in its monopile installation. As with CVOW-C, the observation of mortality events prior to impact or vibratory pile driving activities is evidence that the fish kill events are likely independent of pile driving; 4) Revolution Wind also used the AdBm resonator, a Helmholtz resonator system that reduces noise (Weilgart 2024), as an additional NAS; 5) no fish collections, necropsies, or additional reporting that

¹⁰ The Revolution Wind project was halted by BOEM on August 22, 2025 but was restarted in late September 2025 after a federal judge ruled against the stop-work order, granting developers permission to resume construction.

indicates cause of death were completed for the Revolution Wind events; therefore, it is not possible to make a full comparison of the two fish kill events.

11. PROPOSED RECOMMENDATIONS FOR UNDERSTANDING FISH KILL EVENTS ASSOCIATED WITH OFFSHORE WIND CONSTRUCTION

Why Recommendations Should be Adopted as Requirements

Fish mortality events may be related to construction of offshore infrastructure, including marine energy projects. These events are important to document because they present a unique opportunity for the scientific community to better understand the events and provide managers with necessary information to make recommendations and prevent future occurrences. The fish kills that occurred during the 2024 CVOW-C construction season were unexpected and unprecedented in the peer-review literature. Because the fish kills were unexpected, there was a lack of preparedness to collect information for mass mortality events of non-ESA listed species. The primary lesson learned from the CVOW-C fish kills events and the activities that followed is that there is a need to have an established protocol that is incorporated into the Terms and Conditions of COP approval issued by BOEM to monitor, document, and respond to fish kills associated with offshore wind construction activities. The ability to determine the cause of a fish kill event (e.g., toxic spill vs. low stream flow; Kane et al 1999; Meyer and Barclay 1990; DEQ 2002; Koehn 2022) depends on having established sampling and logistical protocols prior to an event occurring that can be activated when an event occurs (Blazer et al. 2018, Kane et al. 1999, Koehn 2022, Meyer and Barclay 1990, Phelps et al. 2019, VA DEQ 2002). Incorporating these recommendations as requirements into future terms and conditions of COP approval is necessary to determine potential causes of future observations of injury and mortality. Causes of fish kills for non-ESA listed are important to understand because these species may play important roles in commercial and recreational fisheries; ecosystem processes including energy transfer to upper trophic levels; cultural traditions; and tourism. This section presents a set of recommendations to be followed to maximize understanding and potentially help mitigate future fish kill events.

Include a Fish Kill Monitoring and Response Plan with the COP

The details of how the developer will monitor for and respond to a fish kill (i.e., A Fish Kill Monitoring and Response Plan) should be included in the COP submitted to BOEM for review and approval. For example, this could be included as an appendix to the COP as Best Management Practices (BMP), or as part of the Fisheries Monitoring Plan. The Monitoring and Response Plan should detail when and how to properly collect, preserve, analyze, report, store, and share data associated with the fish kill. The recommended specifications for each of these are described below.

Train Staff in Recommended Protocols

Standardized protocols should be established and communicated to onsite staff. Staff should be made aware of the potential for fish kills to occur, how to properly collect and report information, how to properly collect and preserve samples, and with whom to communicate and coordinate in the case of a fish kill. Ideally, trained staff would be specifically dedicated to observing for injured/dead fish.

Coordinate with Regional Facilities

Prior to construction activities, BOEM should require the Lessee to identify regional facilities capable of conducting species identification and necropsies. Through communication and coordination with the facility point of contact, the Lessee should establish a plan for how: (i) species identifications and necropsies would be conducted, (ii) the logistics of sample collection would be managed, and (iii) supplies would be acquired and samples would be shipped in the event of a fish kill.

Establish Lines of Communication and Points of Contact

At CVOW-C, clear communication between NOAA Fisheries, BOEM, BSEE, and Dominion Energy was key to adaptive monitoring of the fish kill events. In future projects, a plan to communicate fish kill information should be required by BOEM and established by the developer. This plan should include what agencies and regional facilities should be contacted and specific points of contact at each entity. Clear lines of communications including POC names, contact information, and what information they should receive and how that information will be delivered should be identified in the plan.

When to Initiate Reporting and Data Collection

If ≥ 10 deceased individuals of non-ESA listed fish are observed within an established shutdown or monitoring zone, the Lessee should report the event to NMFS, BOEM, and BSEE as soon as practicable (taking into account crew and vessel safety). This should occur no later than 24 hours after the sighting. There should be established points of contact at BOEM, BSEE, and NMFS who send/receive this information. The developer should confirm the relevant points of contact prior to reporting and confirm that the reporting was received.

When to Collect Samples

Sample collection should be required as a condition of BOEM's COP approval going forward; to date, sample collection has not been required. To minimize the effect of fish drifting and duplicate counting of the same fish, counts should be made in a single day (VA DEQ 2002).

Furthermore, if possible, sample collection should occur on a day when the vessel is heading back into port and it is possible to ship samples upon arrival at the port. This will minimize the time between sample collection and analysis. Although this may limit sample collection, it will help ensure that samples collected are in good condition once they arrive at the facility and can yield useful information. Tissues that are not properly preserved run the risk of being “as good as no tissues” (Kane et al. 1999) or may act to confuse or mislead the examiner (DEQ 2002).

What Data to Collect

The following data should be provided in each report: (1) location (latitude and longitude); (2) time of day, (3) Quantity of fish and area impacted, (4) Distance from offshore wind construction activity, (5) comments on the condition of the fish (dead, dying, or decaying; lesions or hemorrhaging), (6) behavior, if moribund (e.g., gulping, erratic circular swimming, etc. as clinical observations of fish before necropsy can assist in determining cause (Yanong 2003)), (7) photos of the event, and (8) a timeline of any particular activity that may have caused the event (Kane et al. 1999, Meyer and Barclay 1990, and VA DEQ 2002), (9) water quality data if available. Descriptive observations are preferred over diagnostic observations, as mechanisms may not be obvious in the moment without laboratory tools and techniques (Kane et al. 1999). Collections of fish should be sufficient to capture a random sampling of any species impacted including appropriate sexes, age classes, and relevant sizes. A sufficient sample size (ideally a minimum of $n=30$ per size class, but this will depend on the size of the fish kill event) of individuals should be collected for necropsy (Brussolo 2018). Labeled, left-facing, lateral as well as dorsal photographs that include a ruler or some other object to provide a measure of size should be taken to indicate any injuries or marks at time of collection, especially if fish will be packed and shipped prior to necropsy, as shipping may result in damage to the specimens that is unrelated to the event.

Preserve Specimens for Necropsy in a Manner that Maximizes the Information they can Yield

Preservation of specimens for necropsy in a manner that minimizes physical damage is essential. The method(s) of sample preservation should be planned in coordination with the regional facility in advance (DEQ 2002). Chilling is the preferred method of preservation because this will optimize the examiner's ability to visualize the appearance of fish tissues and isolate/identify disease agents. Fresh dead fish placed in plastic bags and refrigerated or cooled on ice for short periods of time can provide more information in a necropsy than a frozen fish (Yanong 1996, Garces and Pires 2020).

Direct contact between the hypertonic tissues of marine fish and ice should be minimized because this can lead to freshwater uptake and result in bloating and disfigurement of fish carcasses. Fish should be wrapped in sealed plastic bags and placed in coolers with ice packs wrapped in newspaper or paper towels. Crumpled newspaper should line the bottom and fill any

empty space of the cooler to keep the samples lifted from any melted water. If only ice is available, it should be placed in plastic bags to prevent direct contact with samples.

Freezing should only be used in cases in which the destruction of tissues or cells is not important. For example, freezing may be appropriate when the tissues are thought to be harboring parasites, chemicals, or toxins. In these instances, specimens should be frozen as soon as possible to avoid overgrowth of the contaminant. Freezing/thawing cycles with fish should be avoided due to potential impacts on tissues. If freezing with dry ice is required, enough dry ice should be used to keep the sample frozen for over 24 hours, allow for shrinkage, be wrapped in heavy paper, and only be used with Styrofoam containers. (Meyer and Barclay 1990; DEQ 2002)

Conduct Necropsy Analyses

Histological samples and microscopic examinations should be included in the necropsy. Necropsy should include true auditory injury/pathology study which includes an evaluation of the lateral line (Morris et al. 2003; NASEM 2011; Uribe et al. 2018). If stomach content analysis is conducted, NEFSC protocols should be followed (Link and Almeida 2000).

Maintain Records of All Phases of Construction Activities

One of the potential factors that may have been involved in the CVOW-C fish kills was the pressure levels of the compressors that fed the free air delivery of the bubble curtains during operation. While current DBBC protocol typically involves starting the curtains with only a few compressors for the flushing and pressure test phases before moving on to all compressors for the full operating pressure, limitations are involved as the hoses for the DBBC must have sufficient air to fully fill the hoses and cannot start at too low of a pressure. Additionally, pressures and air flow rates of these interim phases are not typically provided in the submitted DBBC reports. Pressure levels associated with flushing, pressure testing, and operation of the bubble curtain should be logged, as well as timing of when bubble curtains are turned on. This will enable a detailed evaluation of fish kills in relation to bubble curtain operation. Well maintained records will also allow comparisons across projects.

Monitor for Fish Kills Using Advanced Technologies

In order to obtain a more comprehensive collection of fish kill data at future projects, if it occurs, when >1 observation of dead fish is made at a project, it is recommended that additional monitoring methods be initiated and maintained for the remainder of the construction activities potentially associated with the fish kill. These could include monitoring with optical instruments mounted on aerial drones that can evaluate a broader field of view; implementation of subsurface optical technologies (e.g., drop cameras; cameras mounted on autonomous underwater vehicles or remotely operated vehicles) that can observe dead fish that are on the seabed (i.e., affected fish

that lack swim bladders); and/or monitoring with active acoustics mounted on a small USV, AUV, ROV, or a glider. It is further recommended that PAM data be collected at all projects to enable the characterization of the sound field during potential fish kill events.

Store Data and Enable Cross-Agency Data Accessibility

Data associated with a fish kill event should be saved and stored by BSEE or BOEM in a single database that is shared with NMFS.

Initiate Bubble Curtain Operations with a Soft Start to Deter Fish

Evidence from the literature indicates that gas bubble trauma associated with hydraulic system operations can negatively affect fish, and it is possible that bubble curtain operations may have played a role in the CVOW-C fish kills. Further, some research suggests that bubble curtains can elicit a deterrence effect for some fish species (e.g., Pacific herring, Hollarsmith et al. 2025). Given this, a soft start to bubble curtain operations (i.e., gentle increase of bubble curtain flow rate and pressure) should be considered as a mitigation method to deter fish from the area prior to full operational mode (which would occur before pile driving soft-start). Although the pressure-testing and flushing (that is currently done prior to pile driving) is effectively a soft start to the bubble curtain, a soft start to bubble curtain operations is not currently performed for the purpose of deterring or protecting fish. A soft start to bubble curtain operations must not interfere with the effectiveness of the bubble curtain, however.

12. FUTURE RESEARCH DIRECTIONS

Many questions remain surrounding the CVOW-C fish kills. This section recommends future work that will aid the understanding of future fish kill events. An enhanced understanding of these events could prevent future fish kill events and/or mitigate the stressors that may have led to the events.

Further Retrospective Evaluation of the Events at CVOW-C and Revolution Wind

Further retrospective evaluation of the fish kill events at the two affected projects in 2024 would be valuable. This could include examining similarities in the patterns observed, the species affected, the equipment used, and other operational considerations.

Species Physiology

Evaluate whether species lacking swim bladders, such as flatfish, skates, and rays, are similarly impacted but remain on the seafloor. Differences between sexes, size classes, and/or age classes could also be evaluated. The species that were noted by the observers were thought to be uniquely impacted by the set of circumstances that led to this string of mortality events, but these were opportunistic sightings with species that are likely to float when injured or dead.

Spatial Dynamics

Further examination of the life history patterns of the affected species (Atlantic croaker and spot) would expand understanding of whether individuals were engaged in specific behaviors, such as spawning or seasonal migration that made them particularly vulnerable to disturbance. These questions could be addressed through a more thorough literature search or additional data collection efforts using passive acoustic monitoring or other survey methodologies.

Temporal Dynamics

Investigating why the mortalities ceased during July would be helpful to determine action to mitigate future recurrences, whether this was due to species behavior/distribution/abundance, piling energy, bubble curtain flow rate, or something else.

Fish Drift

Data characterizing current speed and direction during piling and on meteorological buoys could be used to further study drift patterns of dead fish observed at far-field distances from piling.

Bubble Curtain Analyses

Experiments that examine species-specific effects caused by bubble curtain operation would advance understanding of whether DBBC operation could have contributed to the fish kills. Specific questions of interest include: how does flow rate (including increase in flow rate), radius of the bubble curtain configuration, hole size, or other bubble curtain variables affect the response or injury of fish that encounter the bubble curtain. Notably, a small number of dead fish were occasionally observed within 100 m of a monopile during pressure testing of the bubble curtain, and subsequent observations of many dead fish (e.g., 2,500) occurred while the DBBC was operating at full pressure. Future research should evaluate whether a “soft start” or gentle increase of bubble curtain flow rate and pressure (i.e., addition of compressors) could prompt fish (e.g., ESA-listed, non-ESA listed, commercially/recreationally valuable, etc.) to leave the area (e.g., Hollarsmith et al. 2025) around a monopile without causing injury, potentially preventing large

mortality events once the bubble curtain reaches higher or full pressure throughout the construction process.

Characterization of Particle Motion

A better understanding of changes in particle motion associated with pile driving and DBBC activities would be valuable. All fish species are capable of detecting the particle motion component of noise (Popper et al. 2019b) and a deeper understanding about how particle motion is affected by construction activities and whether these changes in the soundscape could be associated with types of the acoustic traumas observed at CVOW-C require further investigation.

Literature Synthesis

Although a peer-review literature search was conducted, a more comprehensive literature search that includes both peer review, grey literature, and direct communication with developers is warranted to determine whether there are any reports of these events elsewhere in the world and what, if any, reporting requirements for non-ESA listed (or other national or international endangered designation) exist elsewhere for similar construction projects. Because more wind projects are being installed each year, it is possible that additional reports could emerge over time.

13. POST SCRIPT REGARDING CVOC-C FISH KILL EVENTS IN 2025

In the summer of 2025, as this report was being finalized, two additional fish kill events were observed at CVOW-C. On 8 July 2025, PSOs observed 40 deceased Atlantic croaker during the pre-clearance period prior to vibratory pile driving to install monopile G3E16. Additionally, on 9 July 2025, approximately 200 dead Atlantic croaker were observed during vibratory pile driving for the installation of monopile G3F16 at CVOW-C. Dead fish were observed floating upside down, 50m from the pile. Active predation of the dead fish was observed.

14. ACKNOWLEDGEMENTS

We wish to thank several entities that openly shared information and data with us that made many of our evaluations possible including: Dominion Energy, Bureau of Ocean Energy Management, Virginia Institute of Marine Science, North Carolina State University, and The Nature Conservancy. Discussions with Brandon Jensen (BOEM), Thomas Moorman (BOEM), and Alexandra Schneider (BOEM) were invaluable in the development of this report. We are also grateful to our reviewers, Michael Jech (NEFSC), Sue Tuxbury (GARFO), Doug Christel (GARFO), Julie Crocker (GARFO), and Jaclyn Daly (OPR) for their thoughtful comments that improved this report.

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