A Final Project Report to:
Industry Advisory Board of the Science Center for Marine Fisheries.
Title: Impacts of Electromagnetic Fields (EMF) on Benthos
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Statement of problem.
An electrical current traveling along a conductor creates an electro-magnetic field (EMF). The presence of a magnetic field can also induce current in an electrical conductor. This phenomenon was first described in 1820 by the Danish scientist Hans Christian Orsted. Nerves are electrical conductors – nerve impulses move along a neuron as a result of movements of ions across the nerve membrane. It is reasonable to expect that an EMF, such as that produced by buried transmission cables servicing wind farms on the continental shelf, would influence nerve net function at the individual organism level in the benthos. The quantitative relationship is, however, not clear.

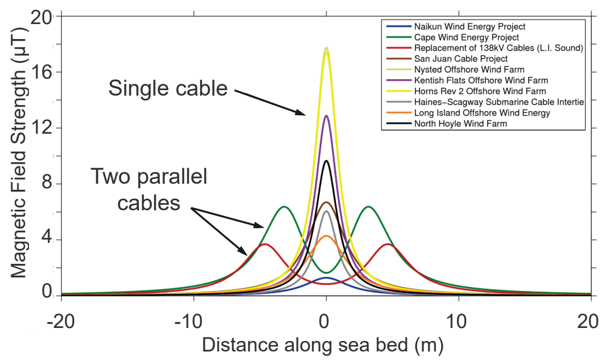
With full build out on the Mid Atlantic Shelf wind farms with require several thousand miles of high voltage DC transmission lines, a number that will inevitably increase as the options develop to move the technology into deeper water and the desire for additional "green" energy increases to serve national demand and develop long term options to combat greenhouse gases and associated climate change. How large will the associated permanent modification be to the background EMF fields across the ocean bottom and, indeed, the water column above? The local EMF environment on the continental shelf is a mix of contributing magnetic fields, starting with that of the Earth (fixed in orientation and between two poles) and varying all the way down to the fields produced by the nervous transmissions of individual animals whose movements alter the orientation and magnitude of the overall EMF. The unit of measurement of a magnetic field is the microTesla (μT), a unit of magnetic flux density. The Earth's natural field is ~51.3 μT. What is the strength of EMF associated with transmission line? A DC cable transmitting a constant 330 MW (1175 Amps) has a magnetic field of ~65 μT, a value that is a 27% higher than the Earth's natural field, but this is limited to the proximity of the cable. Transmission lines have burial specifications to avoid damage by mobile fishing gear and/or exhumation related to storm driven sediment transport. The associated overburden provides both physical protection and field insulation. The nature of EMF strength at the sediment-water interface is addressed below. Note that future wind development includes discussion of floating platforms in deeper water. This introduces questions of transmission lines in the water column, both in terms of entanglement and environmental impact.

When considering the impact of EMF on living organisms, it is important to note that individual neurons are insulated to ensure the integrity of each nerve impulse and resulting muscular action in isolation from all others. So the nature of the imposed EMF environment on nerve transmission is also a subject of some debate – this is addressed later in this report.

A review of known impacts of EMF on marine organisms is addressed in the annotated bibliography section of this report. In brief, most of the published material focuses on fish and larger, mobile benthic organisms such as crab and lobsters. But the majority of biomass in the benthos is infauna, notably clams. We have found only two studies that focuses directly on impacts on clams, otherwise, there is a notable lack of studies on infauna and EMF. A lack of knowledge of the impact of EMF on benthic biota served as the stimulus for this review.

What is the nature of the EMF associated with transmission cables?

This is illustrated in a figure in SEER (2022) review of EMF Field Effects on Marine Life, modified from the original in Normandeau et al (2011[1]). It is included herein. The important points are that the burial depth dampens the EMF signal at the sediment water interface (note the scale on the vertical axis with maximum values in the 4-18 μT range) and that signal decays with distance away from the line of the cable. The final swath of influence is between 5 and 10 m wide. None the less the signal endures for the entire length of the cable.



Spatial distribution of the magnetic field strength on the seabed from existing and proposed OSW AC cables (figure adapted from Normandeau et al. 2011).

What do we know about nerve transmission and EMF?

The mechanisms of nerve transmission have been known for over 85 years. Indeed, the Nobel Prize for Medicine in 1936 was awarded to Sir Henry Hallett Dale and Otto Loewi for their work on the chemical transmission of nerve impulses (focusing on how signals are transmitted at nerve junctions). In 1963 the Nobel Prize for Medicine was awarded Andrew Huxley and Alan Hodgkin for their work describing how nerve signal are transmitted along nerve fibers and between cells as electrical currents and by employing chemical substances as signal transmitters at the end of nerve fibers. Our knowledge of nerve function emanates from these studies. As noted earlier, nerve fibers are also insulated by a myelin sheath, thus isolating one nerve impulse from another. Recent work by Isakov et al (2018) examined human stem cells and pathology focusing on how a generated signal drives an action in a targeted cell. This is fundamental to understanding how muscles are stimulated to contract, and thus how animals move. Isakov et al (2018) concludes that "cell-with-neuron interactions are regulated by the strength of the electromagnetic fields", that is the magnetic field generated by the transmission of the electrical nerve impulse, and that the integrity of the insulating myelin sheath was paramount in the entire nerve-muscle system functionality. Again, to quote Isakov et al (2018) "our model reveals that a 50% demyelination increases the field strength by 0.35 $\times 10^{-12}$T, while a complete demyelination increases it by 0.7 $\times 10^{-12}$T*"*. To place these statement in context we again return to the strength of the Earth magnetic field at ~51.3 μT and the values in the figure above describing EMF distribution around a major electrical conductor buried in the seabed.   The values proffered by Isakov et al (2018) are one million times smaller than background EMF and the changes induced by conductor EMF. In summary, the nerve to tissue interface is very, very sensitive to myelin sheath integrity and even minor trauma can arguably disrupt normal nerve function.

[1]Normandeau et al (2011). Effects of EMFs from Undersea Power Cables on Elasmobranchs and other Marine Species (Report No. BOEMRE 2011-09). https://tethys.pnnl.gov/publications/effects-emfs-undersea-power-cables-elasmobranchs-other-marine-species

Water column versus benthos: should we expect a uniform organismal response?
Marine biota have evolved in the presence of magnetic fields, and we have argued above that the integrity of the nerve – muscle system is critical to organismal function. Any mobile organism might thus have the ability to both orient to ambient EMF and respond to changes in such fields. Benthic species are more limited; infauna are effectively fixed positions with respect to the EMF field. So we should not expect the same order of response among water column and benthic infauna. Molluscs are predominantly benthic and infauna, and have very simple nerve nets that coordinate all actions. Muscle contractions (the active process of contraction) are innervated by a single or short burst of nerve impulses. Clams have special muscles called "catch muscles" that require only infrequent innervation to work, but they are critical to keeping clams closed. We do not know how marginal changes in EMF influence "catch muscles". In summary, we know relatively little about how EMF impacts individual infauna at the physiological level.

A brief history of EMF studies with marine species.
The seminal works on the impact of EMF on marine organisms start with the contributions of the late Adrianus Kalmijn. In the early 1970's he discovered how elasmobranch fishes such as sharks and rays detect electric fields using pores in their snouts. These pores are called the Ampullae of Lorenzini. These structures are sufficiently sensitive to allow discrimination of the electric fields produced by prey organisms against a background of the Earth's magnetic field, hence aiding the targeting of prey, and navigation. Kalmijn's work provided the basis for subsequent observational and studies of how behavior of select organisms changes in the presence of atypical EMF fields. An annotated bibliography of recent contributions on EMF and marine species is provided later in this report. A brief summary of findings is follows.

General reviews of magnetoreception in fishes, and focused studies of skates and lobsters are offered by Formicki et al (2019) and Hutchison et al (2020) respectively – both are detailed in the following literature review section. Formicki et al (2019) provide a reasoned summary as follows: "While observational studies have examined the impacts of EMF (in terms of orientation, intensity and gradients) at various stages of development including gametes, embryonic development, embryonic and larval motor function, directional reactions of embryos and larvae, orientation of fishes, and mechanisms of magnetic field reception," the authors conclude that "understanding of the mechanisms of magnetic sense in fishes and its relevance for ecological outcomes highlights that further progress requires more detailed research." As noted earlier, exposure to the Earth's magnetic field argues that natural EMF may well have been a selective pressure over evolutionary time in a broad array of organisms, so a response to EMF is to be expected in some marine organisms. Salmonids use magnetic fields for navigation, as arguably do turtles and spiny lobsters. Sharks, skates and rays use EMF to seek out prey. Several studies at real world EMF intensities expected in the vicinity of undersea cables suggest minimal to no negative impact on fishes in the field. As with all "cause and effect" studies the results from atypically high exposure intensities in experimental systems (a few are in the bibliography) can elicit responses, but these can be argued to be artifacts of experimental design and not very informative.

A lesser number of studies with lobsters and crabs suggest both physiological and behavioral impacts, but the employed strengths of the EMF fields are somewhat higher than naturally occurring or, arguably, that encountered in close proximity to buried transmission cables in the field.

There are two contributions examining EMF and clams. Stankevičiūtė et al (2019) exposed Baltic clam (*Limecola balthica*) to 1 mT – a 20 fold increase of the Earths field – for 12 days and noted subsequent cell nucleus abnormalities in gill cells in clams. Jakubowska-Lehrmann et al (2022) explored the effect of static magnetic field (SMF) and electromagnetic field (EMF), at values usually recorded near submarine cables, on the bioenergetics, oxidative stress (reduced immune response), and neurotoxicity (toxic to the structure and function of the nervous systems) in the cockle (clam) *Cerastoderma glaucum*. The clams were exposed over a period of 8 day to a field strength of 6.4 mT (greater than the Earth's magnetic field strength by a factor of ~100). Of interest among their findings is that, after exposure to EMF, a significant inhibition of acetylcholinesterase activity was observed. Acetylcholine is a neurotransmitter – it carries nerve "messages" through nerve cells to muscles. Acetylcholinesterase is an enzyme that breaks down acetylcholine. It is found at the junction of nerves and muscles (the synapse) where it serves to terminate the transmission of the nerve message to the muscle – it turns the muscle stimulus off. So EMF at elevated levels interrupts the cessation of the nerve to muscle signal. This is a thoughtful study and addresses impacts on the basic mechanisms of nerve transmission. It emphasizes the need for additional studies

In general, there is very little information on benthic infauna – a most surprising situation given their proximity to buried cables.

The next section is an annotated bibliography. Given the limitations of focused benthic information to date we conclude with a section describing a relatively simple experimental approach using surfclams as a target organism, that can contribute relevant data to this poorly examined field of study. Such an experiment, or series of experiments may be suitable for discussion with federal and/or industry agencies as a vehicle to provide information relevant to EMF impacts on the mid Atlantic shelf.

Annotated bibliography of recent contributions on EMF and marine species.

This bibliography is arranged in sections by subject area. Most of the contributions are from 2010 onwards, a few are older. Each reference has a short description of salient points and a link is provided should the reader seek more detail from the original contribution. Most links can be accessed by simply clicking the link. If this does not work then copy and paste the link into your web browser and it should take you directly to the complete article. The sections are as follows:

1. EMF and cables
2. EMF and marine organisms: Historical contributions
3. EMF and nerve transmission
4. EMF: General reviews of impacts on marine systems
5. EMF: Field observational studies
6. EMF and fish
7. EMF and fish larvae
8. EMF: Focused studies of sharks, skates and rays
9. EMF: Benthos crustacea
10. EMF: Benthos infauna
11. EMF: Turtles and endangered species

1. **EMF and cables**

- Several of the general reviews (#4 below) include discussions of EMF generation by buried transmission cables. Hutchison et al (2021.A modelling evaluation of electromagnetic fields emitted by buried subsea power cables and encountered by marine animals: considerations for marine renewable energy development. *Renewable Energy,* 177, 72-81. https://doi.org/10.1016/j.renene.2021.05.041) proffer an easy to read discussion of high voltage buried DC cables and the EMF they produce. The authors conclude that EMF is generated at intensities "perceivable by receptive species" and that "An animal moving along a cable route may be exposed to variable EMFs due to varied burial depth and that combined with an animal's position in the water column determines the distance from source and EMF exposure." In summary they acknowledge EMF perception but also illustrate the limited knowledge of effect of EMF.
- Farr et al (2021. Potential environmental effects of deepwater floating offshore wind energy facilities. Ocean & Coastal Management 207. https://doi.org/10.1016/j.ocecoaman.2021.105611)

examines possible impacts and mitigation options in up to 1000m depth deployments. Floating turbines are considered for the 120-1000 m water depth. Impacts are currently considered "speculative". The analysis included EMF, habitat change, noise and water quality. The synthesis of 89 contributions considered the impacts could be mitigated to be low risk if appropriate protocols are adopted.

2. EMF and marine organisms: Historical contributions

- The seminal contributions on elasmobranchs (sharks, skates, rays) are those of the late Adrianus Kalmijn (19330-2021) of the Scripps Institute of Oceanography at the University of California at San Diego (UCSD). The UCSD profile for Kalmijn is at https://profiles.ucsd.edu/adrianus.kalmijn This gives a Publications link to all of Kalmijn's work listed in MEDLINE/PubMed. This can be searched by category (newest, oldest, most cited etc.) As noted earlier, Kalmijn described the Ampullae of Lorenzini in sharks and rays. These are openings in the skin, very small "pits" arranged in clusters that are connected beneath the skin by canals filled with conductive mucous. As would be expected for a system of conductors, the system is insulated by the skin and signals are carried to central clusters of ampullae from which nerves transmit signals to the brain. The distribution of sensory ampullae depends on morphology of the species but is generally arrayed to provide a sensory "field." In sharks the ampullae are arranged around the dorsal and ventral parts of the head and along the sides of the individual. In skates and rays the ampullae are around the mouth, on the ventral side of the body (recall these are dorso-ventrally flattened), and along the dorsal side of the wing margin. These arrays of sensors allow detection of local fields originating from other organisms and other inanimate sources.
- The history of EMF in migratory patterns of animals is not limited to the elasmobranchs. There is a substantial literature on the impacts on bird migration (review in Environmental Health Trust 2022, Biological effects of Electromagnetic Radiation on Birds, https://ehtrust.org/biological-effects-of-electromagnetic-radiation-on-birds/.) In marine systems there is a long history of studies related to anadromous fish migration. This is addressed in section 6 of this review.
- Lohmann, C. & Lohmann, K. (1996. Detection of magnetic field intensity by sea turtles. *Nature,* 380, 59-61. https://doi.org/10.1038/380059a0) offer an early review of the question "Can migratory animals determine their global position by detecting features of the Earth's magnetic field?" They argue that to do this an animal must perceive (at least) two distinct magnetic parameters, each of which must vary in a different direction across the Earth's surface. To that point in time there had been little evidence that any animal can perceive two such magnetic features. But it was noted that several populations of sea turtles undergo transoceanic migrations before returning to nest on or near the same beaches where they themselves hatched, and that along the migratory routes, all or most locations have unique combinations of magnetic field intensity and field line inclination. It had been demonstrated that hatchling loggerhead turtles can distinguish between different magnetic inclination angles. Lohmann and Lohmann reported that turtles can also distinguish between different field intensities found along their migratory route. They concluded that sea turtles possess the minimal sensory abilities necessary to approximate global position using a bicoordinate magnetic map.

3. EMF and nerve transmission

- The basic mechanism of nerve transmission can be found at: https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/Map%3A_Raven_Biology_12th_Edition/42%3A_The_Nervous_System/42.02%3A_The_Mechanism_of_Nerve_Impulse_Transmission.
- Isakov et al (Modeling of inhomogeneous electromagnetic fields in the nervous system: a novel paradigm in understanding cell interactions, disease etiology and therapy. SCIENTIFIC REPORTS (2018) 8:12909. https://doi.org/10.1038/s41598-018-31054-9) present a model of non-

homogenous EMFs that originate from nerve fibers and explore their influence on cells. They argue that cell-with-neuron interactions are regulated by the strength of the EMFs. This is particularly important in neurodegenerative disorders – their model reveals that "a 50% demyelination strength by 0.35 × 10^{-12}T, while a complete demyelination increases it by 0.7 × 10^{-12}T". The values proffered by Isakov et al (2018) are one million times smaller than background EMF and the changes induced by conductor EMF. This is an intense paper to read; the important points in the current context are that the junctions between nerve endings and the targeted muscles are regulated by EMF, that integrity of the myelin sheath around the axon is critical in ensuring that nerves function as transmitters, and that any degeneration of the myelin sheath makes nerve function highly susceptible to very small EMF.

- Bertagna et al (Effects of electromagnetic fields on neuronal ion channels: a systematic review. Ann N Y Acad. Sci.. 2021 Sep;1499(1):82-103. doi: 10.1111/nyas.14597. Epub 2021 May 4.) reviews 22 recent (past two decades) contributions but with focus on human systems. It is relevant because the mechanism of nerve transmission is common across the animal kingdom. The authors focus on voltage-gated ion channels (VGCs). These are the channels in nerve surfaces across which ions move as nerve impulses move along the nerve. They concluded that "EMF effects on the neuronal landscape appear to be diverse and greatly dependent on parameters, such as the field's frequency, exposure time, and intrinsic properties of the irradiated tissue, such as the expression of VGCs. Here, we systematically clarify how neuronal ion channels are particularly affected and differentially modulated by EMFs at multiple levels, such as gating dynamics, ion conductance, concentration in the membrane, and gene and protein expression. Ion channels represent a major transducer for EMF-related effects on the Central Nervous System." This is a complex discussion that covers all the ways in which EMF is related to nerve structure and function. Gating dynamics and ion conductance are the rates and mechanisms of moving ions across nerve membranes. Concentration in the membrane is simply that of the ions that are involved in nerve transmission. Gene and protein expression relate how the genetics of the organism play into the nerve transmission process.

4. EMF: General reviews of impacts on marine systems

- SEER: U.S. Offshore Wind Synthesis of Environmental Effects Research. (2022. *Electromagnetic Field Effects on Marine Life*. Report by National Renewable Energy Laboratory and Pacific Northwest National Laboratory for the U.S. Department of Energy, Wind Energy Technologies Office at https://tethys.pnnl.gov/seer .https://tethys.pnnl.gov/seer) is a recent and valuable summary of EMF on marine life. It includes most, but not all of the contributions in the bibliography. It is well written, well-illustrated, and recommended as a good starting point for a reader seeking information on EMF. The authors conclusion is that "So far, behavioral responses of individuals have not been determined to negatively affect a species population, but further research is needed to refine our understanding of the effects of EMFs on wildlife." There are four companion webinars to this report, available at https://tethys.pnnl.gov/environmental-webinars. In addition, there are two research briefs available at https://tethys.pnnl.gov/seer
- Hutchison et al (2020. The interaction between resource species and electromagnetic fields associated with electricity production by offshore wind farms. Oceanography 33(4):96–107, https://doi.org/10.5670/oceanog.2020.409) is included in a special volume of Oceanography (Volume 33(4)) devoted to Understanding the Effects of Offshore Wind Energy Development of Fisheries. This is a comprehensive review of EMF exposure that includes sensory biology, life history theory, and movement ecology. The contribution reviews EMF interactions with benthic, bentho-pelagic, and migratory species, focusing on functional roles of electro- and magneto-reception at different life stages. This listing includes elasmobranchs, fish, lobsters, and crab, but also notes that "Smaller crustaceans and mollusks have received less attention, but cellular responses have been recorded in some bivalves." In short, the data on molluscs is poor. The authors conclude with a statement that "Improving models of future scenarios depends on taking a more

systematic and consistent approach to measuring and modeling alternating current and direct current EMFs and accounting for cable properties and local environmental characteristics." To a large extent the experiments proposed in the final section of this report entitled "**Where to from here**?" provide a template for quantifiable responses of the type sought by Hutchison et al.

- Hutchison et al (2020. Anthropogenic electromagnetic fields (EMF) influence the behavior of bottom-dwelling marine species Scientific Reports (2020) 10:4219 https://doi.org/10.1038/s41598-020-60793-x) focuses on behavioral responses of the American lobster and Little skate to EMF emissions of a high voltage direct current (HVDC) transmission cable, describe an increase in exploratory/foraging behavior in skates and a more subtle exploratory response in lobsters. By directly measuring both the magnetic and electric field components of the EMF emitted by HVDC cables the authors found that there were both DC and AC components. Modelling, restricted to the DC component, showed good agreement with measured results.
- Taormina et al (2018. A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions. *Renewable and Sustainable Energy Reviews,* 96, 380-391.https://doi.org/10.1016/j.rser.2018.07.026**)** focuses on the engineering aspect of cables installation, operation and decommissioning phases, and associated ecological relevance and knowledge. The discussion then moves main knowledge gaps and research needs, and recommendations for better monitoring and mitigation of the most significant impacts. They conclude that ecological impacts associated with cable operations "can be considered weak or moderate, although many uncertainties remain, particularly concerning electromagnetic effects."
- Thomsen et al (2015. MaRVEN - Environmental Impacts of Noise, Vibrations and Electromagnetic Emissions from Marine Renewable Energy (Report No. RTD-K3-2012-MRE). Report by Danish Hydraulic Institute (DHI). Report for European Commission. https://www.researchgate.net/publication/301296662_marven_-_environmental_impacts_of_noise_vibrations_and_electromagnetic_emissions_from_marine renewable_energy) is an EU commissioned product focusing on installation and operation of wind farms. It is not a comprehensive biological review and offers the following on EMF and organisms: "As yet, there is no evidence to enable an assessment of cumulative effects. There have been some studies that suggest that there may be effects on early life stages of fish but other studies have not shown any effects. The lack of information on effects has led to the general conclusion that EMFs from marine renewable energy developments are not harmful. However, this is in the absence of any detailed evidence that biota are not at risk of harm."

5. EMF: Field observational studies

- Love et al. (2016. *Renewable Energy in situ Power Cable Observation*(Report No. BOEM 2016-008). Report by University of California Santa Barbara. Report for Bureau of Ocean Energy Management (BOEM) https://www.boem.gov/2016-008/ or https://tethys.pnnl.gov/sites/default/files/publications/boem-2016-008_0.pdf opportunistically examined behavior and reaction of organisms to both energized and unenergized sea bottom power cables (supplying offshore oil platforms) within the Santa Ynez Unit Offshore Southern California Planning Area. The identical cables stretch several miles from Platforms Heritage, Harmony, and Hondo (at depths to about 326 m) to Los Flores on the mainland. These cables were installed (but not buried to depth as for wind farm cables) concurrently, and thus form a natural experiment, allowing a comparison of an energized power cable with one that is unenergized to determine the potential EMF impacts while controlling for habitat effects. The authors offer four major conclusions:
    - The strength of the EMF along the energized cable was relatively stable over time and along its length, but diminished to background levels about one meter away from the cable.

- There were no biologically significant differences among fish and invertebrate communities between energized cables, pipe, and natural habitat. Only three species of fish showed statistically significant, but slight, differences in densities between the cables and pipe. Plant communities did differ among habitats and within habitats between depths but these differences were almost certainly structure and depth, rather than EMF, related.
- Only one elasmobranch individual was observed during the course of the study that the EMFs generated by these energized cables was either unimportant to these organisms or that at least other environmental factors take precedence.
- Given the rapidity with which the EMF produced by the energized cables diminishes and the lack of response to that EMF by the shallower fish and invertebrates, cable burial would not appear necessary strictly for biological reasons. In this and similar cases, cable burial, at sufficient depth, would be an adequate tool to prevent EMF emissions from being present at the seafloor.

6. EMF and fish

Salmonid fishes that migrate from freshwater to marine systems and subsequently return to freshwater to spawn have been considered as candidates that employ the Earth's magnetic field to enable migration.

- Yano et al (1997. Effect of modified magnetic field on the ocean migration of maturing chum salmon, *Oncorhynchus keta***.** *Marine Biology* **129**: 523–530. https://doi.org/10.1007/s002270050193) investigated the role of magnetic compass orientation in oceanic migrating chum salmon, *Oncorhynchus keta*, off the coast of Kushiro, Hokkaido. Four salmon were fitted with a tag which generated an artificial magnetic field and modified the geomagnetic field around the head of the fish. Initially, the free-ranging salmon with stomach-implanted ultrasonic transmitters were tracked for a period of several hours before the magnetic field was altered for a period of 16 h. The generator produced an alternating magnetic field intensity of about 6 gauss, with polarity which reversed every 11.25 min. There was no observable effect on the horizontal and vertical movements of the salmon when the magnetic field was modified. However, it was noted that salmon slowed their swimming speed significantly before changing direction, regardless of whether the fish were swimming under the normal geomagnetic field or whether they were swimming under the modified field.
- Putman et al (2013). Evidence for Geomagnetic Imprinting as a Homing Mechanism in Pacific Salmon. *Current Biology,* 23(4), 312-316. https://doi.org/10.1016/j.cub.2012.12.041) examined a 56 year data record for Fraser River sockeye salmon movement around Vancouver Island as part of their migratory passage. The proportion of salmon using each route was predicted by geomagnetic field drift: the more the field at a passage entrance diverged from the field at the river mouth, the fewer fish used the passage. Sea water temperature modified the observations: more fish used the northern passage in years with warmer sea surface temperature. None the less the results provided the first empirical evidence of geomagnetic imprinting in any species and imply that forecasting salmon movements is possible using geomagnetic models.
- To follow on Putman et al (2014. Rearing in a Distorted Magnetic Field Disrupts the 'Map Sense' of Juvenile Steelhead Trout. *Biology Letters,* 10, 1-5. https://doi.org/10.1098/rsbl.2014.0169) used simulated magnetic displacements to test orientation preferences of juvenile steelhead trout (*Oncorhynchus mykiss*) exposed to magnetic fields existing at the northernmost and southernmost boundaries of their oceanic range. Fish reared in natural magnetic conditions distinguished between these two fields by orienting in opposite directions, with headings that would lead fish towards marine foraging grounds. By contrast, fish reared in a spatially distorted magnetic field (typical of hatcheries) failed to distinguish between the experimental fields and were randomly oriented. These observations add support to the argument for imprinting in salmonids.

- In a third study Putman et al (2018. Geomagnetic field influences upward movement of young Chinook salmon emerging from nests. *Biology Letters,* 14(2) https://doi.org/10.1098/rsbl.2017.0752) demonstrated that magnetic fields are important as an orientation cue that helps fish determine which way is up when emerging from gravel and that *Oncorhynchus* species are sensitive to the magnetic field throughout their life cycles, and thus guides their movements across a range of spatial scales and habitats.
- In yet a fourth study Putman et (2020. A sense of place: pink salmon use a magnetic map for orientation. *Journal of Experimental Biology,*223(4) https://doi.org/10.1242/jeb.218735) concluded that **"**large-scale movements of pink salmon across the North Pacific may be driven largely by their innate use of geomagnetic map cues. Key aspects of the oceanic ecology of pink salmon and other marine migrants might therefore be predicted from magnetic displacement experiments.
- Wyman et al (2018. Behavioral responses by migrating juvenile salmonids to a subsea high-voltage DC power cable. *Marine Biology,* 165, 1-15.https://doi.org/10.1007/s00227-018-3385-0) used acoustic biotelemetry tracking data to examine movement behaviors and migration success of a magneto-sensitive fish, late-fall run Chinook (LFC) salmon (*Oncorhynchus tshawytscha*), in relation to the energization of a magnetic field-producing subsea power cable, as well as other potentially influential environmental parameters. They analyzed detection records of tagged LFC salmon smolts during their out-migration through the San Francisco Bay before and after the installation of an 85-km high-voltage direct-current transmission cable. They found that cable energization did not significantly impact the proportion of fish that successfully migrated through the bay or the probability of successful migration. However, after cable energization, higher proportions of fish crossed the cable location and fish were more likely to be detected south of their normal migration route. Transit times through some regions were reduced during cable activity, but other environmental factors were more influential. Resource selection models indicated that proximity to the active cable varied by location: migration paths moved closer to the cable at some locations, but further away at others. Overall, cable activity appeared to have mixed, but limited effects on movements and migration success of smolts.
- Formicki et al (2019. Magnetoreception in fish. *Journal of Fish Biology,* 95, 73-91. https://doi.org/10.1111/jfb.13998**)** argue that magnetoreception and sensory systems were one of the first to evolve because they are so widespread in taxa that have both young and old evolutionary roots. Magnetoreception has been studied with respect to fish migration over large distances and in species that are more or less sedentary. While observational studies have examined the impacts of EMF (in terms of orientation, intensity and gradients) at various stages of development including gametes, embryonic development, embryonic and larval motor function, directional reactions of embryos and larvae, orientation of fishes, and mechanisms of magnetic field reception, the authors conclude that "understanding of the mechanisms of magnetic sense in fishes and its relevance for ecological outcomes highlights that further progress requires more detailed research."
- Snyder et al (2019. Evaluation of Potential EMF Effects on Fish Species of Commercial or Recreational Fishing Importance in Southern New England (Report No. BOEM 2019-049). Report by US Department of the Interior (DOI). https://espis.boem.gov/final_reports/BOEM_2019-049.pdf) addresses the potential effects of EMF from undersea power cables associated with offshore wind energy projects on fish species of commercial and recreational importance. Notably, the review was assembled with help of commercial and recreational fishing communities, provides background information about EMF in the environment and the relevance of EMF to fish species of concern in the southern New England area. As with general reviews by Hutchison et al (see #1) above) and SEER (see #4 above) the report contains a comprehensive description of wind farms cable design, installations and associated EMF properties. The discussion offers a very comprehensive status review of sharks, skates, rays, sturgeon and general bony fish for both the pelagic and demersal habitats, but most impacts of energy associated EMF are considered to be

very limited or negligible. The only invertebrate discussed in detail is the lobster. Discussion of infaunal benthos is absent, a reflection (again) of the paucity of knowledge of the impact of EMF on this group.

7. EMF and fish larvae

Section #6 above provides evidence that fish, especially migratory fish, have the ability to sense EMF. Does this extend to the larval stages that, depending on species, can drift over extended distances during their early life stages?

- Fey et al (2019, Are magnetic and electromagnetic fields of anthropogenic origin potential threats to early life stages of fish? Aquatic Toxicology 209: 150-158. https://doi.org/10.1016/j.aquatox.2019.01.023). exposed rainbow trout embryos and larvae to a static magnetic field (MF) of 10 mT and a 50Hz electromagnetic field (EMF) of 1 mt for 36 days. Neither exposure had significant effect on embryonic or larval mortality, hatching time, larval growth, or the time of larvae swim-up from the bottom. However, both MF and EMF enhanced the yolk-sac absorption rate. Although not related directly to magnetic field effect, it was also noted that larvae that absorbed yolk-sacs by the time of swim-up were less efficient in taking advantage of available food at first feeding (i.e., obtained smaller weight at age). That indicates the importance of processes affecting yolk-sac absorption rate.
- Cresci et al (2019 Atlantic Haddock (*Melanogrammus aeglefinus*) Larvae Have a Magnetic Compass that Guides Their Orientation. iScience 19, 1173–1178, September 27, 2019. https://doi.org/10.1016/j.isci.2019.09.001) investigated whether Atlantic haddock larvae passively drift or orient using the Earth's magnetic field. In the North Sea, haddock main spawning areas are located close to the northern continental slope. Eggs and larvae drift with the current across the North Sea. However, fish larvae of many taxa can orient at sea using multiple external cues, including, it was hypothesized, the Earth's magnetic field. The authors observed the behavior of 59 and 102 haddock larvae swimming in a behavioral chamber deployed in both the Norwegian North Sea and in a magnetic laboratory. In both in situ and laboratory settings, where the magnetic field direction was modified, haddock larvae significantly oriented toward the northwest. The authors conclude that haddock larvae orientation at sea is guided by a magnetic compass mechanism that is potentially variable for other populations throughout the North Atlantic." Note that this is a region specific conclusion to the Norwegian North Sea. None the less the observations support the assertion that if the EMF made the magnetic compass less effective or ineffective then the larvae would be compromised.
- Cresci et al (2022. Magnetic fields produced by subsea high-voltage direct current cables reduce swimming activity of haddock larvae *Melanogrammus aeglefinus* PNAS Nexus, 2022, 1, 1–7. https://doi.org/10.1093/pnasnexus/pgac175) followed on from their 2019 report with a focus on haddock larval swimming when exposed to EMF in the intensity range produced by high voltage direct current (DC) subsea cables. Atlantic haddock larvae disperse through areas where DC subsea cables are present or planned and impacts of EMF could alter their dispersal. After exposure to anthropogenic EMF fields, both swimming speed and acceleration of 78% of the tested haddock larvae were significantly reduced. The authors note that while the study also provided insights about magneto-sensitivity in marine larval fish, the subject in general remains poorly understood.
- Cresci et al (2022. Magnetic fields generated by the DC cables of offshore wind farms have no effect on spatial distribution or swimming behavior of lesser sand eel larvae (*Ammodytes marinus*). Marine Environmental Research. Volume 176: 105609. https://doi.org/10.1016/j.marenvres.2022.105609) focuses on EMF in the North Sea and larvae of the keystone species, the lesser sand eel (*Ammodytes marinus*). They examined behavior of 56 lesser sand eel larvae in an experiment simulating the scenario of larvae drifting past a DC cable at an environmentally relevant exposure of 150-50 μT. This did not affect the spatial distribution of lesser sand eel larvae in a tank 50 cm long, 7 cm wide and 3.5 cm deep. Nor did the EMF alter their

swimming speed, acceleration or distance moved. They concluded that static EMF from DC cables would not impact behavior of lesser sand eel larvae during the larval period of their life. although it does not exclude the possibility that later life stages could be affected.

8. **EMF: Focused studies of sharks, skates and rays**

The seminal works here are those of Kalmijn as noted in #2 EMF and marine organisms: Historical contributions. Everything else in this section essentially builds on the foundations offered by Kalmijn.

- Sisneros, et al (1998. Response properties and biological function of the skate electrosensory system during ontogeny. *Journal of Comparative Physiology A,* 183, 87-99. https://doi.org/10.1007/s003590050237) examined the response properties of clearnose skate (*Raja eglanteria*) electrosensory primary afferent neurons at various life stages. These included pre-hatch embryos (8–11 weeks), post-hatch juveniles (1–8 months), and adults (>2 year). During ontogeny there was systematic changes that demonstrated (a) encapsulated embryos exhibit ventilatory movements that are interrupted by a "freeze response" when presented with weak uniform fields corresponding to natural fish predators, allowing the embryo to mediate predator detection and avoidance; (b) reproductively active adults discharge their electric organs at rates near the peak frequency sensitivity of the adult electrosensory system to facilitates electric communication during social behavior. The authors suggest that life-history-dependent functions such as these may shape the evolution of the low-frequency response properties for the elasmobranch electrosensory system.
- Normandeau et al (2011). Effects of EMFs from Undersea Power Cables on Elasmobranchs and other Marine Species (Report No. BOEMRE 2011-09). https://tethys.pnnl.gov/publications/effects-emfs-undersea-power-cables-elasmobranchs-other-marine-species . This is the report from which the earlier figure of EMF field strength with respect to proximity of the conducting cable is reprinted. It is a very extensive literature review up to 2011. It includes sections on electro- and magneto-sensitivity of a variety of marine organisms, including elasmobranchs (sharks and rays) and other fish species, marine mammals, sea turtles, and invertebrates. The appendices list all of the prior work and are comprehensive. Elasmobranchs (sharks, skates, rays), where studied, are generally sensitive to EMF, as are some lampreys, eels, catfish, ratfish, salmonids (see also #6 above), and sturgeon. A number of marine mammals are argued to be sensitive to EMF based on anatomical or theoretical evidence: these include fin and pilot whales and some dolphin species. Loggerhead, green, Kemp's Ridleys, and leatherback turtles have all been suggested to the sensitive to geomagnetic fields. Molluscs are poorly studied with respect to EMF: one sea slug species showed behavioral and physiological response to EMF, while a Mediterranean mussel also showed physiological responses.
- Bedore and Kajiura (2013. Bioelectric Fields of Marine Organisms: Voltage and Frequency Contributions to Detectability by Electroreceptive Predators. *Physiological and Biochemical Zoology,* 86(3), 298-311. https://doi.org/10.1086/669973.) catalogued the magnitude and frequency of the electric field produced by 11 families of marine organisms. Behavioral responses of elasmobranch fishes to weak electric fields have been well studied. The objective of this study was to examine electric fields that simulate the natural electric field of prey items, that is the "signal" produced by prey that are detectable by searching predators, to quantify the ranges at which elasmobranch predators are capable of utilizing EF for detection. There was little variation across wide taxonomic groups. Invertebrate electric potentials ranged from 14 to 28 μV. Elasmobranchs ranged from 18 to 30 μV. Invertebrates and elasmobranchs produced electric potentials smaller than those of teleost fishes, which ranged from 39 to 319 μV. All species produced electric fields within the frequency range that is detectable by elasmobranch predators.
- In a subsequent report Newton and Kajiura (2017 Magnetic field discrimination, learning, and memory in the yellow stingray (*Urobatis jamaicensis*). *Animal Cognition,* 20, 603-614.

https://doi.org/10.1007/s10071-017-1084-8) focused on magnetoreception in wild caught yellow stingrays, *Urobatis jamaicensis*. Individuals were conditioned to respond to a magnetic stimulus with a food reward in order to elicit foraging behaviors. The stingrays learned to discriminate the magnetic stimuli. Memory probes were conducted at intervals between 90 and 180 days post-learning criterion, and six of eight stingrays trained completed the probes with a ≥75% success rate and minimum latency to complete the task. These results show the fastest rate of learning and longest memory window for any batoid (skate or ray) to date. The study demonstrated that yellow stingrays, and possibly other elasmobranchs, can use a magnetic stimulus as a geographic marker for the location of resources and is an important step toward understanding whether these fishes use geomagnetic cues during spatial navigation tasks in the natural environment.

9. EMF: Benthos crustacea

- Five contributions are reviewed, and their conclusions do not offer a consistent picture of EMF response. Boles and Lohmann (2003) suggest that adult spiny lobster may have the ability to use magnetic fields in navigation. Taormina et al. (2020) suggest that juvenile European lobsters are unaffected by EMF at ten-fold the intensity of the Earths field. In two contributions Scott et al (2018 and 2020) concluded that EMF had impact on both physiology and behavior of the crab *Cancer pagurus*, these studies employing EMF exposure varying between 250 μT and 2.6 mT-recall that the Earths EMF is 51.3 μT. Harsanyi et (2022) suggest EMF can induce deformity in European lobster early life history stages, but the exposure intensity was over 50 fold higher than the intensity of the Earth's magnetic field
- Scott et al (2018. Understanding the effects of electromagnetic field emissions from Marine Renewable Energy Devices (MREDs) on the commercially important edible crab, *Cancer pagurus* (L.). Marine Pollution Bulletin. Volume 131, Part A, 2018: 580-588. https://doi.org/10.1016/j.marpolbul.2018.04.062.) examined the effects of simulated EMF on the edible crab (*Cancer pagurus*) using both physiological and behavioral parameters. They noted how EMF declines away from conductors. Currents between 850 and 1600 Amperes (A) tend to be found in undersea cables consequently producing an electromagnetic field of around 3.20 millitesla (mT) (1,600 A) in a perfect wire, but EMF fields diminishes away from the source, with values of around 0.32 mT and 0.11 mT at 1 m and 4 m respectively. Exposure to EMF (6h at 2.6 mT for physiological studies, 10 min exposure for behavior studies) had no effect on haemocyanin (a respiratory pigment in the blood) concentrations, respiration rate, activity level or antennular flicking rate. EMF exposure significantly disrupted haemolymph (blood equivalent in invertebrates), L-Lactate (a chemical buffering the cell processes during high exercise, it maintains stability in the cell) and D-Glucose (energy source in the cell) natural circadian rhythms. Crabs showed behavioral response to EMF: there was a clear attraction to EMF exposed shelter (69%) compared to control shelter (9%) and they significantly reduced their time spent roaming by 21%. Consequently, EMF emitted from Marine Renewable Energy Devices (MREDs) will likely affect both the behavior and physiology of crabs.
- In a subsequent contribution Scott et al (2021. Exposure to Electromagnetic Fields (EMF) from Submarine Power Cables Can Trigger Strength-Dependent Behavioural and Physiological Responses in Edible Crab, *Cancer pagurus* (L.). *J. Mar. Sci. Eng.* 2021, *9*(7), 776; https://doi.org/10.3390/jmse9070776) extended earlier investigations focusing on of the effects of different EMF strength exposure (250 μT, 500 μT, 1000 μT – generally environmentally appropriate) on edible crab (*Cancer pagurus,* Linnaeus, 1758) employing the same physiological and behavioral parameters. EMF strengths of 250 μT were found to have limited physiological and behavioral impacts. Exposure to 500 μT and 1000 μT were found to disrupt the L-Lactate and D-Glucose circadian rhythm and alter hemocyte (blood cell) count. Crabs showed a clear attraction to EMF exposed (500 μT and 1000 μT) shelters with a significant reduction in time spent roaming. The authors concluded that EMF will likely affect crabs in a strength-dependent manner thus highlighting the need for reliable in-situ measurements.

- Boles and Lohmann (2003). True Navigation and Magnetic Maps in Spiny Lobsters. *Nature,* 421, 60-63. https://doi.org/10.1038/nature01226) proffered the argument that animals are capable of true navigation if, after displacement to a location where they have never been, they can determine their position relative to a goal without relying on familiar surroundings, cues that emanate from the destination (such as chemical cues), or information collected during the outward journey. At the time of publication only a few animals, all vertebrates, had been shown to possess true navigation. This was the first report of a marine invertebrate, the spiny lobster *Panulirus argus,* orienting reliably towards a capture site when displaced 12–37 km to unfamiliar locations, even when deprived of all known orientation cues during displacement. Little is known about how lobsters and other animals determine position during true navigation. To test the hypothesis that lobsters derive positional information from the Earth's magnetic field, lobsters were exposed to fields replicating those that exist at specific locations in their environment. Lobsters tested in a field north of the capture site oriented themselves southwards, whereas those tested in a field south of the capture site oriented themselves northwards. These results imply that true navigation in spiny lobsters is based on a magnetic map sense.
- Taormina et al. (2020. Impact of magnetic fields generated by AC/DC submarine power cables on the behavior of juvenile European lobster (*Homarus gammarus*). *Aquatic Toxicology,* 220, 105401 https://doi.org/10.1016/j.aquatox.2019.105401) examined the potential impact of static and time-varying EMF on the behavior of recently settled juvenile European lobsters (*Homarus gammarus*) using two different behavioral assays. Day-light conditions were used to stimulate the sheltering behavior and facilitate the video tracking. Juvenile lobsters did not exhibit any change of behavior when submitted to an artificial EMF gradient (maximum intensity of 200 µT – that is four times the intensity of the Earth's magnetic field) compared to non-exposed lobsters in the ambient magnetic field. Additionally, no influence was noted on either the lobsters' ability to find shelter or modified their exploratory behavior after one week of exposure to anthropogenic magnetic fields (225 ± 5 µT) which remained similar to those observed in control individuals. Static and time-varying anthropogenic EMF, at these intensities, do not significantly impact the behavior of juvenile European lobsters in daylight conditions. This does not preclude the option that other life stages may respond differently.
- Harsanyi et (2022. The Effects of Anthropogenic Electromagnetic Fields (EMF) on the Early Development of Two Commercially Important Crustaceans, European Lobster, *Homarus gammarus* (L.) and Edible Crab, *Cancer pagurus* (L.). *Journal of Marine Science and Engineering,* 10(5), 18.https://doi.org/10.3390/jmse10050564**)** examined the effect of EMF on ovigerous (egg bearing) female European lobster, *Homarus gammarus* (L.) and edible crab, *Cancer pagurus*. The exposure was to static (Direct Current, DC) EMFs (2.8 mT – over 50 fold higher than the intensity of the Earth's magnetic field) throughout embryonic development. EMF did not alter embryonic development time, larval release time, or vertical swimming speed for either species; however, chronic exposure to 2.8 mT EMF throughout embryonic development resulted in significant differences in stage-specific egg volume and resulted in stage I lobster and zoea I crab larvae exhibiting decreased carapace height, total length, and maximum eye diameter. An increased occurrence of larval deformities was observed in addition to reduced swimming test success rate amongst lobster larvae. The authors suggest that these traits may ultimately affect larval mortality, recruitment, dispersal and population dynamics of *H. gammarus* and *C. pagurus*.

10. EMF: Clams and benthic infauna

- Clams are benthic dominant biota and have nerve nets of varying complexity. That of the clam is remarkably simple by comparison with, for example, a lobster. Clams behavior is limited in scope and dominated by such actions as opening and closing modulated by adductor muscles, burial, feeding, spawning and more, each moderated by nerve function. An interruption of any of these nerve functions would have associated deleterious impacts on general physiology and wellbeing of these organisms. The contributions on benthos vary in focus from genetic and cytotoxic, through biodiversity with whole animal physiology in between.

- Stankevičiūtė et al (2019). Genotoxic and cytotoxic effects of 50 Hz 1 mT electromagnetic field on larval rainbow trout (*Oncorhynchus mykiss*), Baltic clam (*Limecola balthica*)and common ragworm (*Hediste diversicolor*). *Aquatic Toxicology,* 208, 109-117.https://doi.org/10.1016/j.aquatox.2018.12.023) examined the impact of long term exposure to EMF of trout, a clam and a polychaete worm. The exposure was high at 1 mT – a 20 fold increase of the Earths field. Exposure time was 40 days for trout early life history stages and 12 days for the clam and worm. The assay used genotoxicity and cytotoxicity responses – that is cell nucleus abnormalities blood cells in trout, gill cells in clams, and coelomocytes (cells driving the immune system) in worms. While all species demonstrated some response, the most notable was in the clam. The authors state that ...” The present study is the first to reveal the genotoxic and cytotoxic activity of 1 m T EMF in aquatic animals, and, consequently, the first one to report the adverse effect of this factor on common marine invertebrates and early life stages of fish.” The question remains as to the applicability of these findings to field conditions where EMF is much lower.
- Li et al (2023. Offshore Wind Energy and Marine Biodiversity in the North Sea: Life Cycle Impact Assessment for Benthic Communities. *Environ. Sci. Technol.* 2023, 57, 16, 6455–6464. https://doi.org/10.1021/acs.est.2c07797) examined the impact of offshore wind development on marine biodiversity focusing on North Sea installations and life cycle assessments of marine benthos. They concluded that there were no impacts on soft bottom communities, but “artificial reefs” formed by hard substrates around installation foundations doubled species richness and increased abundance by up to two orders of magnitude.
- Jakubowska-Lehrmann et al (2022 Do magnetic fields related to submarine power cables affect the functioning of a common bivalve? https://doi.org/10.1016/j.marenvres.2022.105700) explored the effect of static magnetic field (SMF) and electromagnetic field (EMF), at values usually recorded near submarine cables, on the bioenergetics, oxidative stress (reduced immune response), and neurotoxicity (toxic to the structure and function of the nervous systems) in the cockle (clam) *Cerastoderma glaucum*. The clams were exposed over a period of 8 day to a field strength of 6.4 mT. The authors argued that this would be the maximum exposure in close proximity to a cable carrying a 1500A current. While the experimental approach is commendable, the EMF field strength is greater than the Earth’s magnetic field strength by a factor of ~100. The clams maintained a positive energy balance (so they can grow), but the filtration rate and energy available for individual production were significantly lower in SMF-exposed animals compared to the control treatment. No changes in the respiration were noted but ammonia excretion rate (a barometer of protein as a respiratory substrate, generally considered a stress response when elevated) was significantly lower after exposure to EMF (this suggests a depression of physiological activity). Changes in the activities of antioxidant enzymes (that stabilize metabolic processes) and the lipid peroxidation were not observed however, exposure to both fields resulted in increased protein carbonylation (a barometer of stress). After exposure to EMF a significant inhibition of acetylcholinesterase activity was observed. (What does this mean? Acetylcholine is a neurotransmitter – it carries nerve “messages” from the brain through nerve cells to muscles and is thus important to movement. Acetylcholinesterase is an enzyme that breaks down acetylcholine. It is found at the junction of nerves and muscles (the synapse) where it serves to terminate the transmission of the nerve message to the muscle – it turns the muscle stimulus off). So EMF interrupts the cessation of the nerve to muscle signal. This is a thoughtful study and addresses impacts on the basic mechanisms of nerve transmission. It emphasizes the need for additional studies.

11. EMF: Turtles and endangered species

- The early (1996) contribution of Lohmann and Lohmann (see #2. EMF and marine organisms: Historical contributions) was important in demonstrating that sea turtles have the sensory capability to approximate global position using a bicoordinate magnetic map**.**
- A subsequent contribution by Putman et al, including Lohmann as a co -author, (2015., Magnetic navigation behavior and the oceanic ecology of young loggerhead sea turtles *Journal of Experimental Biology,* 218(7), 1044–1050. https://doi.org/10.1242/jeb.109975 **)** conducted lab-based experiments to determine how hatchling loggerhead sea turtles (*Caretta caretta*) respond to magnetic fields that exist at five widely separated locations along their migratory route, and then studied the consequences of the observed behavior by simulating it within an ocean circulation model. Magnetic fields associated with two geographic regions that pose risks to young turtles (due to cold wintertime temperatures or potential displacement from the migratory route) elicited oriented swimming, whereas fields from three locations where surface currents and temperature pose no such risk did not. Additionally, at locations with fields that elicited oriented swimming, simulations indicate that the observed behavior greatly increases the likelihood of turtles advancing along the migratory pathway. The findings suggest that the magnetic navigation behavior of sea turtles is intimately tied to their oceanic ecology and is shaped by a complex interplay between ocean circulation and geomagnetic dynamics.

Where to from here?

We pose the question " would the addition of line transmission EMF over background EMF influence nerve functions, physiology, growth and survival of benthos, or would EMF exposed animals accommodate to a raised background EMF and simply function "as normal" based on variation around this new baseline?" The literature review does not adequately address this question. Thus we suggest an experimental approach that would be informative.

In situ observational studies of EMF impacts are too compromised by any number of variables, even with attempted Before and After Control Impact (BACI) designs. Critical evaluation requires an experimental approach with limited compromising variables that examine life history and/or behavioral traits that are either binary (yes/no) or simply quantified in response; and an experimental system that mimics both the region of disturbance around/above a transmission cable, including the "gradation" of EMF field moving away from the line of central line of the transmission cable. In the absence of such experimental approaches in the literature, we proffer the following as a logical sequence to examine potential impacts on infauna with special emphasis on clams.

Start with consideration of the initial environmental disturbance – transmission line burial by a jet plough. This leaves a soft "swath" on either side of the buried cable that gradually dewaters as sediment resettles after installation/burial. The obvious focus is on the recruitment process that rebuilds/restores the community to its "precondition" as before cable burial, and we offer clams as example organisms. Experiments should initially address settling and metamorphosing stages because the clam larvae are in the water column, arguably removed from the immediate EMF field. Note that the settling (behavior) and metamorphosing (changing form) larval stage uses much of its energy reserves over the very short time period associated with major morphological change, arguably including a period of no or limited feeding, and perhaps, limited mobility associated with morphological change. So any disruption of the settling/metamorphosis event could have significant impact on an already stressful transition.

We can culture suitable target species in numbers sufficient to design and implement statistically defensible experiments with binary results (yes/no to completion of metamorphosis) or simple percentage metamorphosis. These avoid the compromised observational studies in field situations where natural variation abounds. Any experimental design has a requirement for quantitative deployment and recovery of experimental animals, thus a "contained system" requirement where "containers" are transparent to EMF field. The option here is to employ clams contained in bags of Nytex nylon mesh or similar material in experiments with short time durations (days) allowing replication, and ease of setup. A suitable mesocosm design is proposed.

Consider a mesocosm that is rectangular (elongate) with DC cable either buried in it (along its length, avoiding the wall effect of tank) or below it (easier to construct and maintain but recall the need for EMF transparency). The cable dimensions and electric current should be sufficient to generate an EMF facsimile of that in the field (see the earlier figure taken from Normandeau et al. 2011, also a cautionary note on the employment of elevated EMF strengths in prior studies and how these may compromise final interpretation). A control treatment is needed in any quantitative experiment, so a second identical mesocosm will be required with the ability to turn one off. There will be a sediment overlay of the cable in each mesocosm, ensuring that the sediment type mimics in situ on the continental shelf. The mesocosm "duo" is thus set, but there is an additional requirement to observe actions of organisms exposed to EMF and changes in EMF. This is the approach employed by Kalmijn in his elasmobranch studies – place the fish in the tank, observe, alter the EMF, observe, alter again back to starting EMF, observe, and so on. For the proposed mesocosm the observational capability would be an overhead infrared video camera that can be positioned at any location over the mesocosm. Lighting is critical, experiments should employ reduced intensity parallel to that encountered on the sea bottom. Thus the mesocosm requires a "dark" lab. Thus the needs for infrared video (these are widely available and relatively inexpensive, PI Mann used these nearly 35 years ago for a similar purpose). Video records can be downloaded in real time to a computer with ability to add a time stamp and stop/start/slow playback for any behavioral study. Such computers should be isolated from the mesocosm and enhanced by the usual data backup capability. Again, the intensity of the EMF employed can be chosen from sources as per the figure provide earlier in this text. EMF in the experimental mesocosm can be measured by a magnetometer, there are a number of options on Amazon, and any experiment would require that the spatial nature of the EMF in the mesocosm be mapped, the question being how does the EMF "decay" away from the central line over the DC line (the analog to the field situation described in the figure earlier in the text)?

Experimental options to quantify EMF impacts

The above described mesocosm provides the environment to assay percentage metamorphosis of a known initial number of pediveliger (ready to metamorphose stage) clams (surfclams as an example, or other target species) arrayed along the mesocosm parallel to the conductor and EMF field (these are experimental replicates) and across the EMF field (treatments to develop dose repose curve as the dose is measured by the magnetometer as described above) in the mesocosm. An experimental duration of 24-48 hours should suffice (there is an abundance of expertise culturing clams through early life history stages). A second mesocosm with the EMF turned off is the experimental control. Repeating the experiment with pediveligers that come from more than one larval culture temporal sequence avoids the statistical limits of pseudoreplication. Such experiments can be run in quick succession and produce data is short time frames.

As a follow on from the above, a large larval culture provides an abundance of early post settlement/metamorphosed juveniles, and these can be used at varying times in subsequent growth to examine EMF response using the same spatial array, along and across the EMF mesocosm, and record time to bury and burial depth (assuming they bury). These data can be both binary (do they or do they not bury) and quantitative (how long to bury and to what depth).

If burial is observed then a third tier of experiment follows that focuses predation, who survives and who does not with respect to position in the EMF field when a predator is introduced to the system? The predator array can include crabs and/or gastropods and/or fish, either individually or in combination. Each predator would have its own behavioral search time frame, so consideration would be required to optimize video recording search patterns and time required to search. None the less such experiments would allow the developmental of matrices of stage/size of prey versus stage/size of predator. This is a considerable matrix of options, but arguably quite tractable given the proposed experimental setup. Consider herein the possible complication that the predators also react to the EMF field.

Finally there is yet a fourth tier of experiments using the metamorphosed clams. We are unaware of the long term developmental impacts on juvenile clams under constant exposure. Prior work (see literature review) suggests cellular abnormalities may arise, but these are at elevated EMF. Once initiated the above described experiments are simple to maintain (they can be set as flow through tank experiments). Clams can be sacrificed at regular intervals for an extended duration and subsequently examined for pathology. Do we observe anomalous development? Is there a delay in first maturation and so on? Again, there is an abundance of expertise in this field in mid Atlantic laboratories.

Molluscs, has noted earlier, have relatively simple nerve nets. Development of this nerve net occurs during early life history, thus focus of the impact of EMF on this fragile life history stage is warranted. The above described mesocosm/EMF spatial array could easily be employed to examine hatching success (both percentage hatching and tie to hatch) with gastropod eggs. Either *Polynices* (moon snail) or *Busycon* (whelk) egg cases from the same mass provide suitable experimental targets. A post hatch behavioral index (can they move, how do they move) can also be used as proxies for any nerve development impairment (note earlier described behavior studies with crabs). Spatial constraint of egg masses and hatched juveniles would be required for such an experiment, but Nytex or similar nylon netting should suffice.

All of the above address the recruitment and re-establishment of communities after cable installation, plus a protocol for extending studies into the early post recruit life history. The studies are mostly short time scale and tractable with control options, can be quantified and avoids complications of in situ studies. If they collectively fail to identify any EMF impact, then there probably is not any significant EMF associated impact in the field.