# Marine invertebrates and sound

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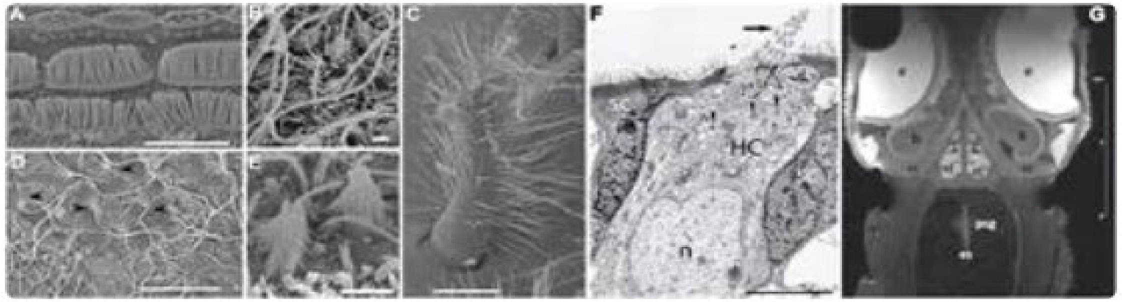


REVIEW
07 March 2023

**Marine invertebrates and noise**

Frontiers in Marine Science > Marine Biology > Research Topics

## Marine Invertebrates and Sound



Solé M, Kaifu K, Mooney TA, Nedelec SL, Olivier F, Radford AN, Vazzana M, Wale MA, Semmens JM, Simpson SD, Buscaino G, Hawkins A, Aguilar de Soto N, Akamatsu T, Chauvaud L, Day RD, Fitzgibbon Q, McCauley RD and André M (2023)
**Marine invertebrates and noise. Front. Mar. Sci.** 10:1129057. doi: 10.3389/fmars.2023.1129057

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- Basics of marine invertebrate bioacoustics
- Techniques used to study invertebrate bioacoustics
- Sound perception
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- Marine noise pollution
  - Sources (Natural, Biological, and Anthropogenic Origin)
- Effects of noise on marine invertebrates (adults, larvae, eggs populations and ecosystems): Physical, Behavioural, and Physiological effects
- Gaps and perspectives


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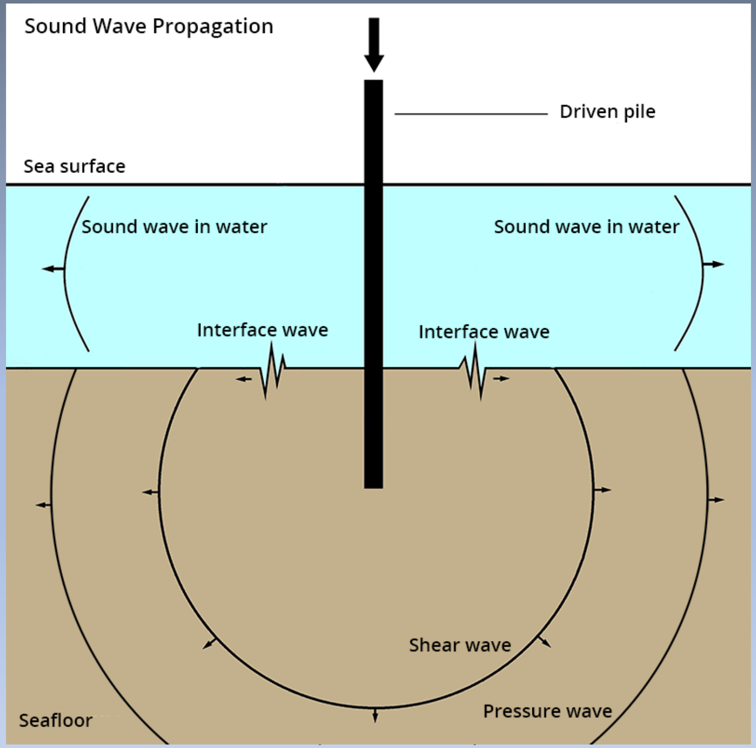
# Role of sound for marine invertebrates

- Sound travels **five times faster in water** (ca. 1500 m/s) than in air (ca. 340 m/s)
- Long-distance communication in water, but also implies a **long-distance impact of noise on aquatic animals**
- **Important sensory modality for marine organisms -** other senses (vision, smell or taste) limited - information loss in marine ecosystems
- Scientific knowledge of the biological significance of sound perception and production in marine invertebrates is **scarce**
- Acoustic signals for **communication** about **predators, prey, territorial defence, social and sexual behaviour, and identity.**
- **Detect sounds** both as part of **communication** and to **make use of acoustic cues in the environment** (e.g. **settlement and habitat choice)**

# Basics of marine invertebrate bioacoustics

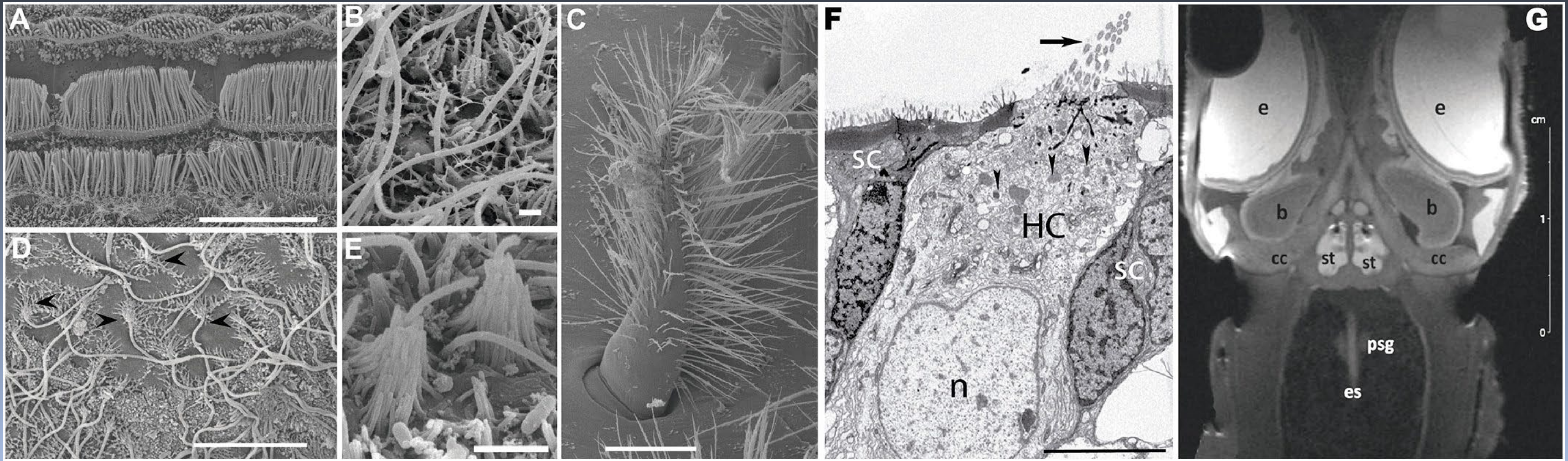
- **Wide diversity of taxa** (crustaceans, cephalopods, gastropods, bivalves, bryozoans, echinoderms, cnidarians, tunicates, zooplankton...)
- Variety of **habitats** including the **water column**; **close to, on, or within the seafloor**
- **Acoustically complex**, with **multiple routes for sound and vibrations** to travel **within seafloor** and the **water column** as well as the i**nterface** between them
- Vibrations in many ways. Water-borne acoustic energy has a **sound pressure** component and a **particle motion** component

Diagram of sound waves generated by pile driving. Sound traveling down the pile creates waves in the water (sound waves), in the sediment (pressure and shear waves), and at the sediment-water interface (interface waves). Waves can transit from sediment to water and vice versa. Image modified from Dr. Anthony D. Hawkins. (https://dosits.org/animals/effects-of-sound/anthropogenic-sources/pile-driving/)



# Techniques used to study marine invertebrate bioacoustics

## Imaging techniques




**Imaging Techniques. (A–E): Scanning Electron Microscopy. (F): Transmission Electron Microscopy. (G): Magnetic Resonance Imaging. (A–F): Different types of sensory epithelia (hair cells) depending on the marine invertebrate group (A, F, G: Cephalopods. (B, E): Cnidarians. C: Crustaceans. D: Gastropods)** (Solé et al. 2011, 2016, 2021)

(Solé, M., Kaifu, K., Mooney, T. A., Nedelec, S. L., Olivier, F., Radford, A. N., et al. (2023). Marine invertebrates and noise. Front. Mar. Sci. 10. doi: 10.3389/fmars.2023.1129057)

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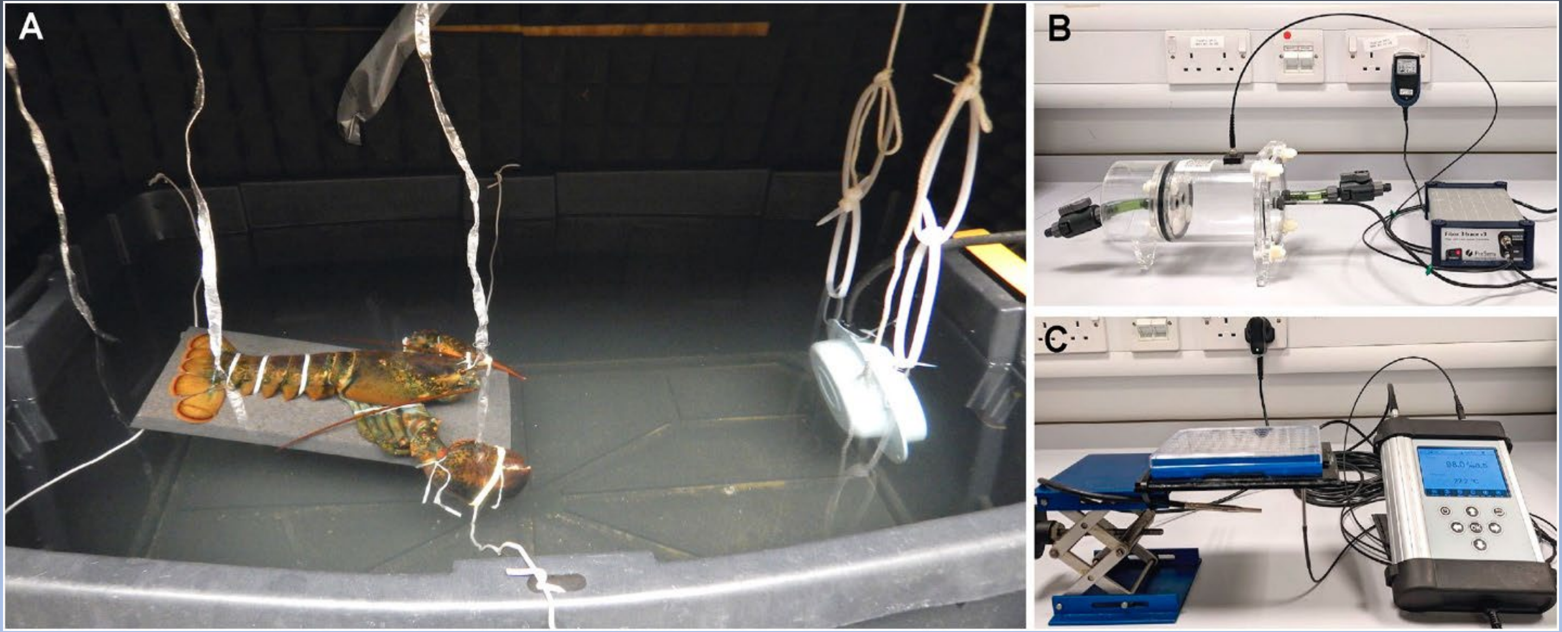
# Techniques used to study invertebrate bioacoustics

**Electrophysiology**

**Respirometry**

Solé, M., Kaifu, K., Mooney, T. A., Nedelec, S. L., Olivier, F., Radford, A. N., et al. (2023). Marine invertebrates and noise. Front. Mar. Sci. 10. doi: 10.3389/fmars.2023.112905712




**(A) Electrophysiology. (B, C): Respirometry. (A): Evoked potential hearing test of an American lobster (*Homarus americanus*)** (Dr. Youenn Jézéquel (Woods Hole Oceanographic Institution) **(B): Respiration set-up for adult invertebrates; (C): Plate set-up used for larvae and gametes** (Dr. Matthew A. Wale (School of Applied Sciences, Edinburgh Napier University)

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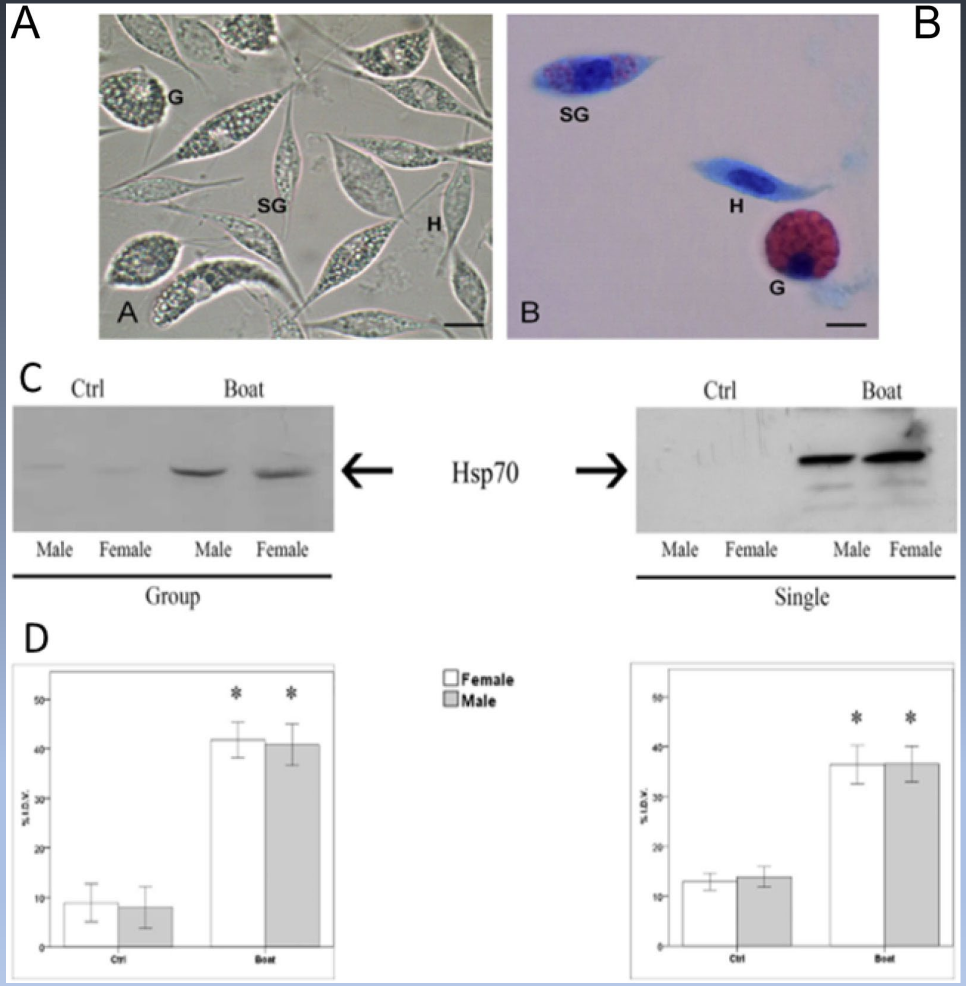
# Techniques used to study invertebrate bioacoustics

## Cellular–biochemical–molecular aspects

- Haemocyte count (THC)
- Heat shock proteins expression
- Total protein concentration (PT)
- Phenoloxidase activity (PO) in
  cell-free haemolymph
- Glucose haemolymphatic
- Changes in enzyme activities




Light Microscopy. Haemocytes of the spiny lobster *Palinurus elephas* **(A)** no staining and **(B)** stained with May–Grünwald–Giemsa. H: hyalinocytes; SG: semigranulocytes; G: granulocytes. Scale bars: **(A, B)** = 8 µm. Effect of the acoustic stimuli on the expression levels of the protein Hsp70 in *P. elephas*; **(C)** Representative western blot of Hsp70 levels in single and grouped animals. **(D)** Integrated density value (% IDV) of the Hsp70 protein bands. Data are the means ± standard error (N = 18 control and N = 18 test specimens). Asterisks represent significant differences between CTRL and BOAT condition (*= $p < 0.01$). (Filiciotto et al., 2014).

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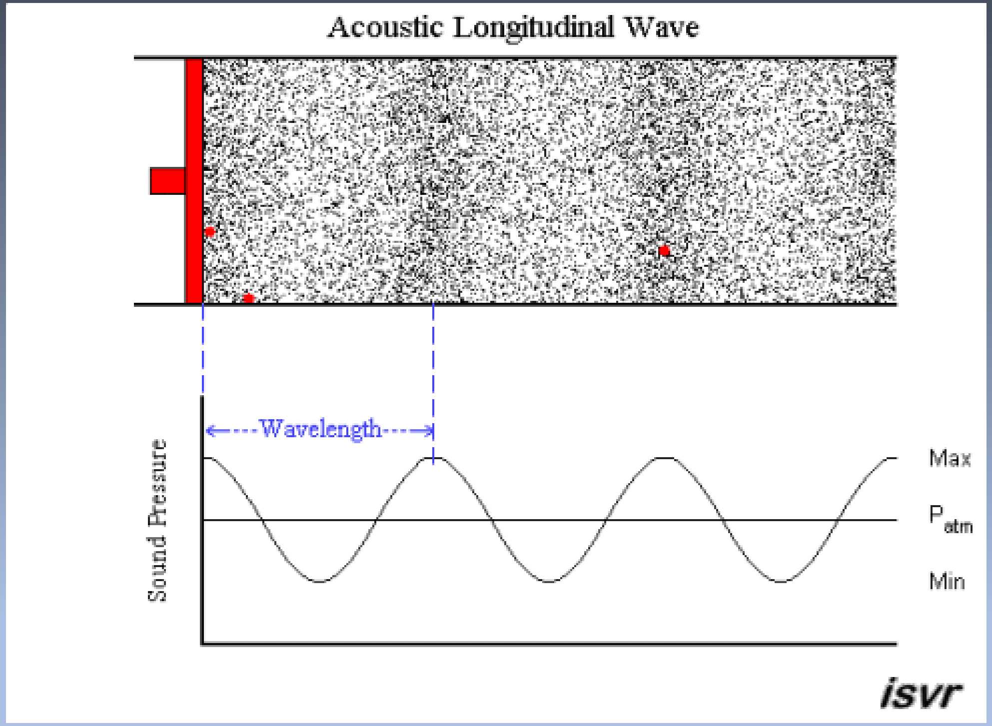
# Sound perception

## Physic aspects: Acoustic pressure vs. particle motion

Sound is a physical phenomenon: mechanical oscillation of particles in an elastic medium, capable of provoking an auditory sensation

Sound propagates in the form of pressure waves: the sound waves are variations of pressure which are transmitted through space and time resulting from movement of the particles moving themselves from their position of equilibrium

Frequency: oscillations per second that are produced in the particles from the medium with respect to their position of equilibrium (Hertz ).




https://resource.isvr.soton.ac.uk/spcg/tutorial/tutorial/Tutorial_files/Web-basics-nature.htm

# Sound perception

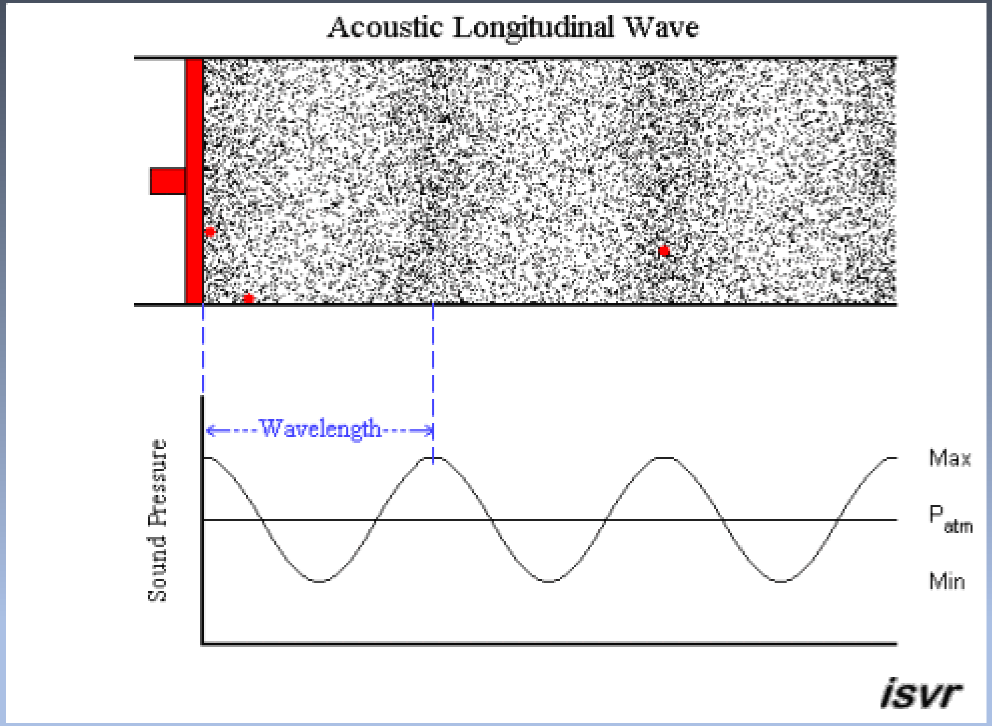
## Physic aspects: Acoustic pressure vs. particle motion

Underwater hearing may involve the detection of the pressure component, the particle motion component, or the detection of either of these two sound field components

Invertebrates
lack of information concerning the invertebrates reception of the sound process

statocysts and epidermal lines - in low-frequency sound reception (ciliated sensory cells- mechanoreceptors)

statocyst would work as a low-frequency accelerometer-like detector and would be able of detecting the component of the sound pressure field

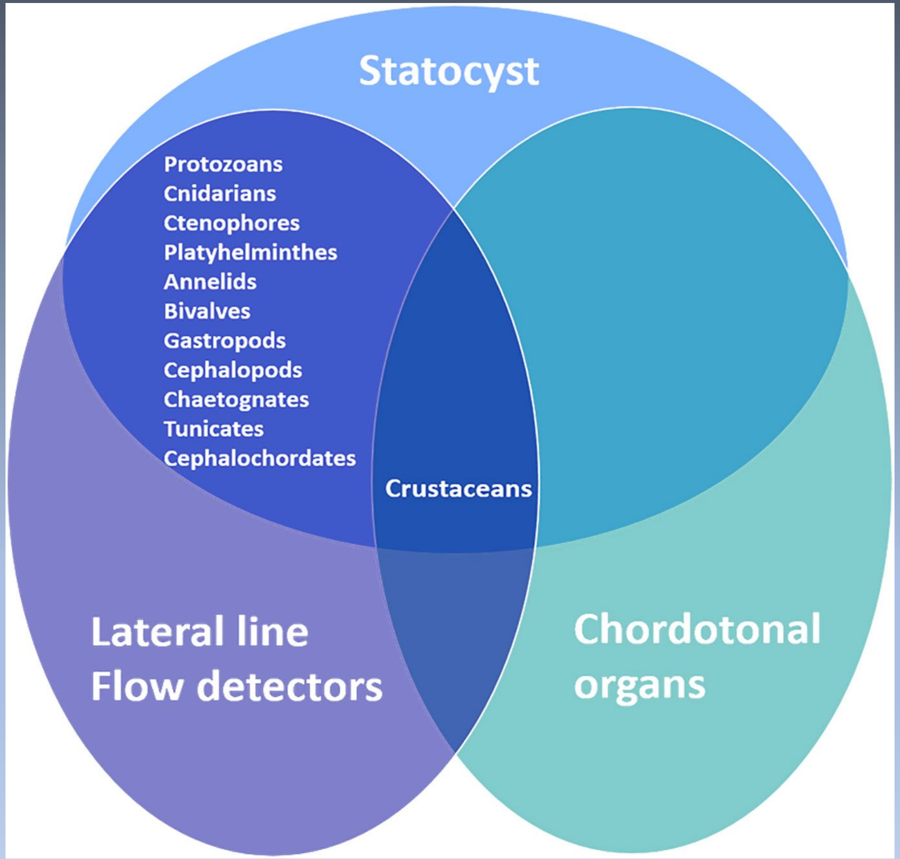



https://resource.isvr.soton.ac.uk/spcg/tutorial/tutorial/Tutorial_files/Web-basics-nature.htm

# Receptor Systems

**Biological aspects: Cilia-based mechanosensory systems**

Invertebrates can detect underwater sound (i.e., of mechanical disturbance of water) through three types of sensory systems: the **body superficial receptor systems**, the **internal statocyst receptor system** and the **chordotonal organs**

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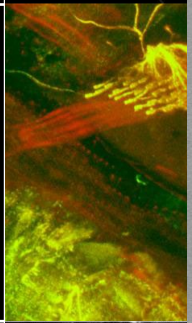
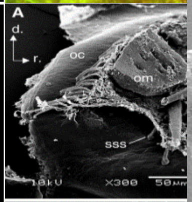
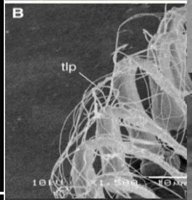
Receptor Systems

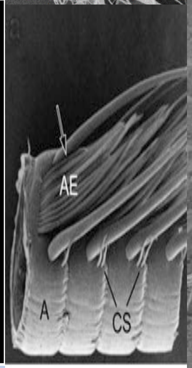
Marine Invertebrates

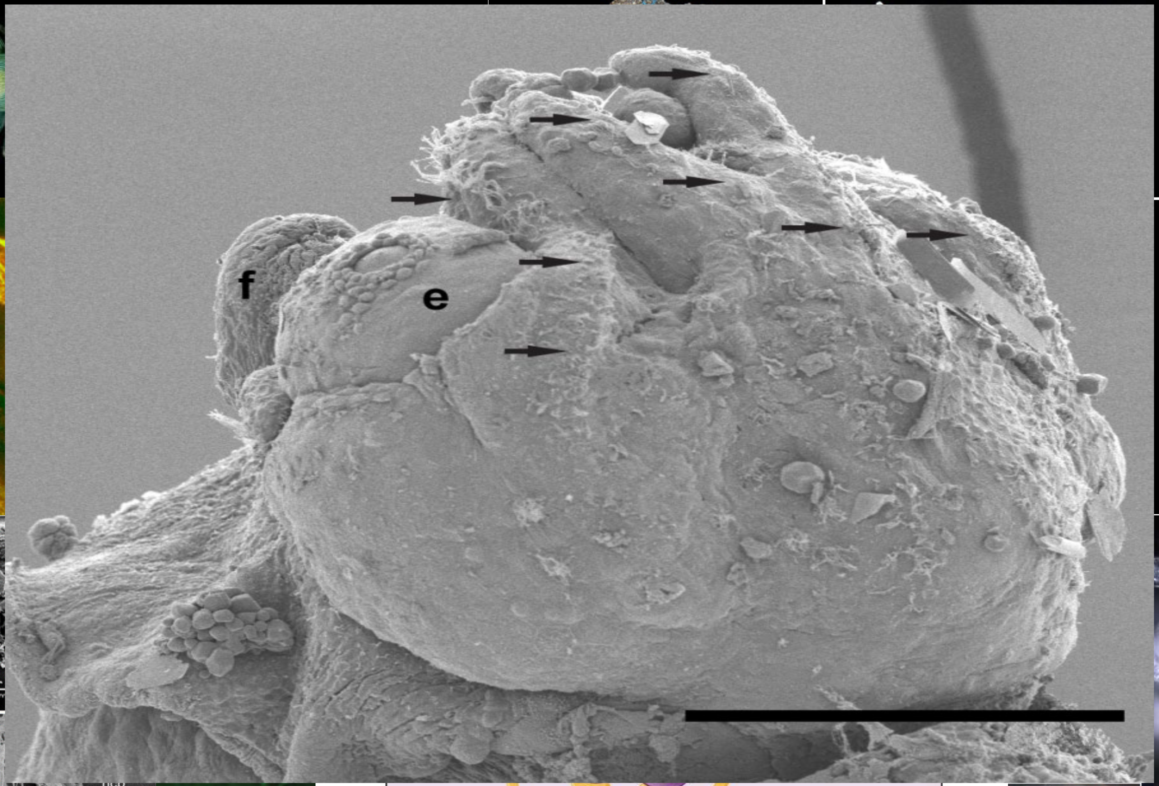
| | CRUSTACEANS | MOLLUSCS | CEPHALOPODS | CNIDARIANS | ECHINODERMS |
|---|---|---|---|---|---|
| CHONDRO-TONAL ORGANS | | | | | |
| STATOCYST | | | | | |
| WATER FLOW DETECTORS | | | | | |

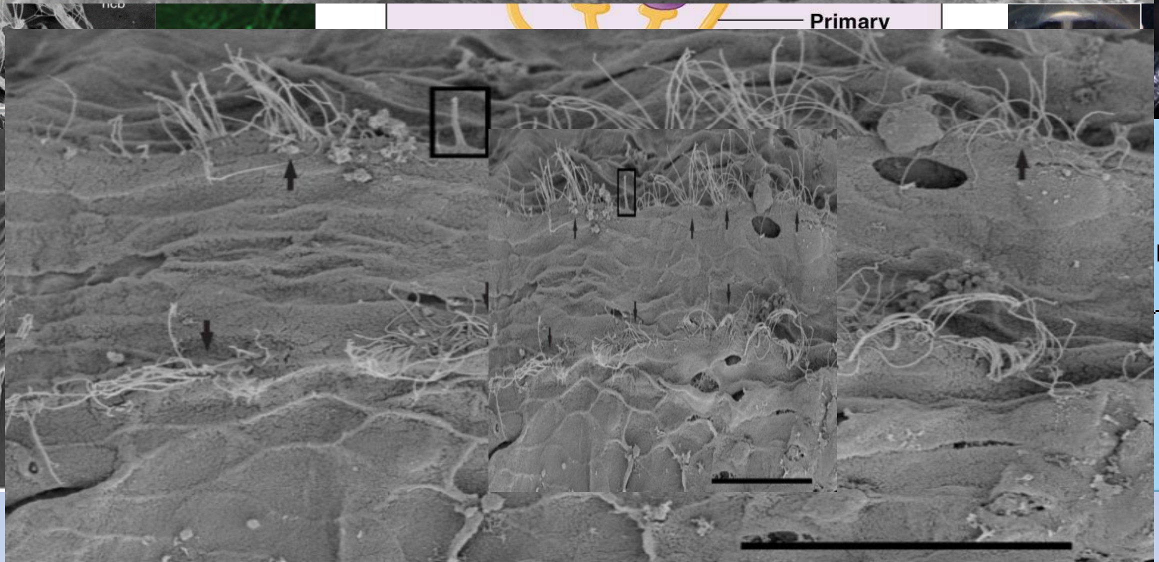


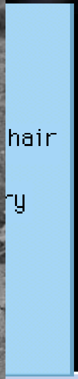











# Sound production

**Bivalves:**

- Mussels: **snapping** sound (stretching and breaking byssal threads) (Ubirajara Gonçalves et al., 2020)
- Valve movements (expelling water and faeces ,"**cough**" by the contraction of the two valves of their shell (sharp **"crack"** followed by a **long puffing noise** as the two valves close) (Di Iorio et al., 2012)

**Echinoderms:**

**-**Long-spined sea urchin (*Diadema antillarum*) **crackling** sounds by **stridulation of its stiff spines** and with a **special feeding structure, the Aristotle's lantern**. (Uses the five teeth of the lantern to scrape kelp or invertebrates from the substrate)
Additionally, **calcified skeleton** act as a **resonator (Helmholtz resonator**) (Radford et al., 2008).
Grazing *Kina* urchins increase ambient sounds level 20 – 30 dB during the sunrise/sunset (Radford et al., 2010)

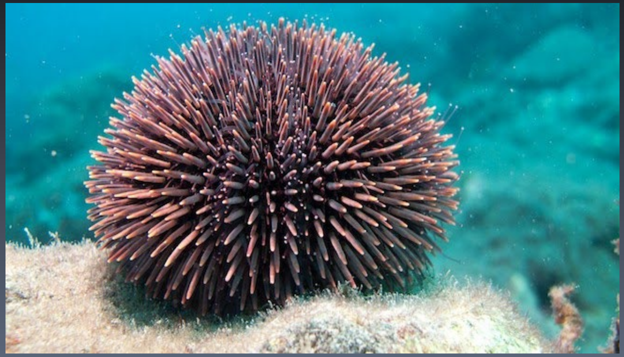
**Crustaceans:**

- Snapping shrimp: **explosive clicks** (territorial behaviour, stun prey or interspecific opponents ) Au and Banks, 1998; Versluis et al., 2000; Kim et al., 2009)
- Stomatopod mantis shrimp (*Hemisquilla californiensis*) and American lobsters *(Homarus americanus):* low-frequency **rumblings**
- European spiny lobsters *(Palinurus elephas*): **ultrasonic signals.** Stridulating organ (**plectrum**) and rigid file to produce **audible rasps** (anti-predator responses) (Patek and Caldwell, 2006; Staaterman et al., 2011, Buscaino et al., 2011, Jézéquel et al., 2020)
- California spiny lobsters (*Palinurus interruptus*): **pulsatile rasps.** Frictional structures at the base of each antenna (potential predators)
- American lobsters **carapace vibrations** (simultaneously contracting the antagonistic remotor and promotor muscles (base second antena)
- Red swamp crayfish (*Procambarus clarkii*): sound signals (territorial role) (Buscaino et al., 2012)
- European lobsters (*Homarus gammarus*) male **buzzing sounds** (intraspecific communication during agonistic interactions) Jézéquel et al., 2018; 2020)

# Sound production

## Sea Urchin
(crackling sounds)

Link DOSITS/
Sound courtesy of Craig A Radford, University of Auckland



## Snapping Shrimp
(explosive clicks)

Link DOSITS/
Sound courtesy of Paul Perkins, NUWC Engineering, Test and Evaluation Department.

## Spiny lobster
(pulsatile rasps, stridulation)

Link DOSITS/
Sound courtesy of Sheila Patek.

## Ghost crab
(rapping)

Link DOSITS/
*Sound courtesy of David Clayton, Sultan Qaboos University (Oman).*

## Mantis Shrimp
(low-frequency Rumblies)

Link DOSITS/
Sound courtesy of Sheila Patek.

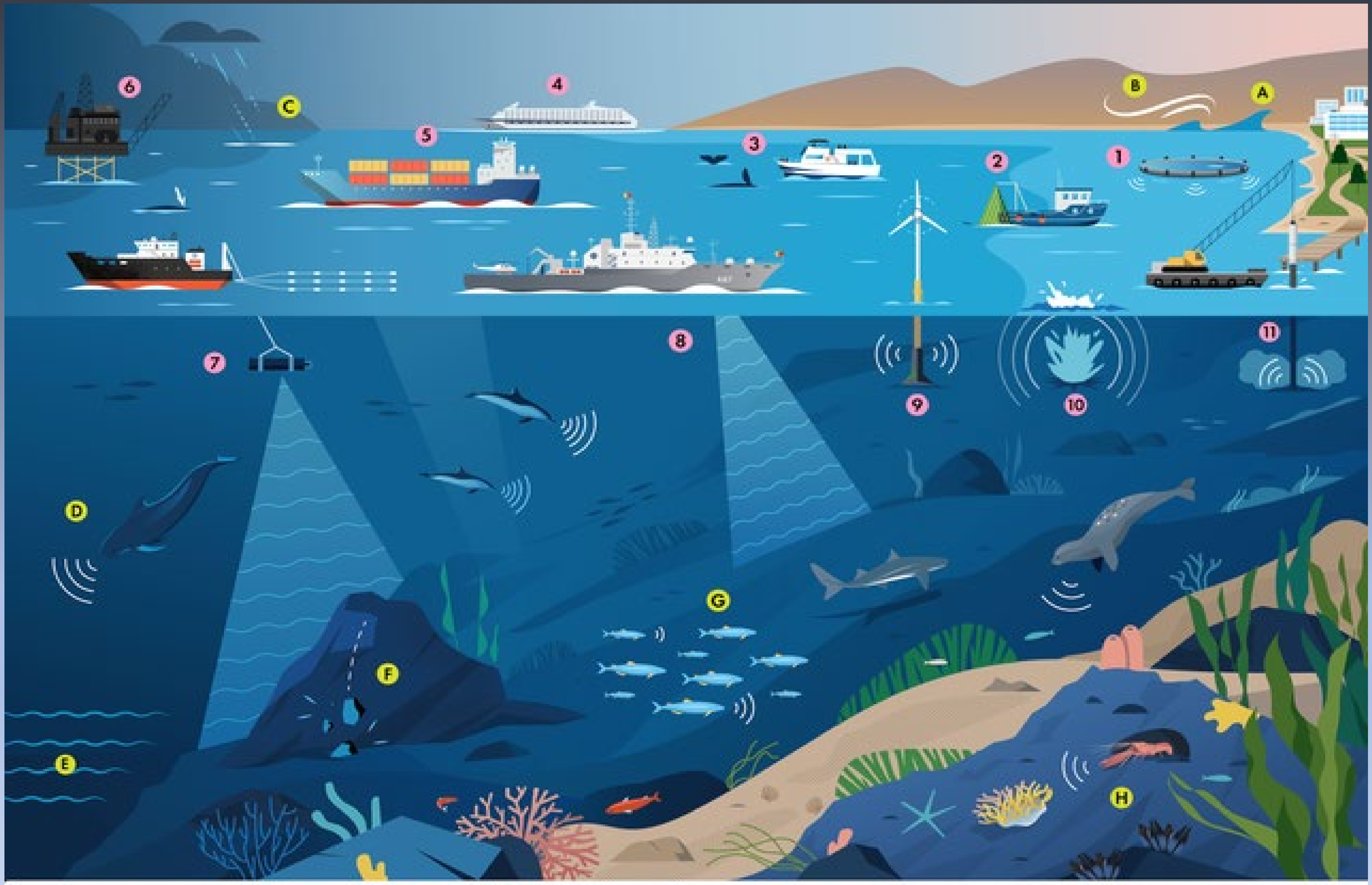
## Scallop
(“couging”)

Link DOSITS/
*Sound courtesy of Lucia DI IORIO, CHORUS*

# Marine noise pollution

**Sound sources**

**(Natural, Biological and Anthropogenic Origin)**




Dozier, A., European Marine Board, JONAS Project. (2021). The Ocean Soundscape. Available at https://www.amydozier.com/todays-ocean-soundscape.

# Marine noise pollution

## Underwater anthropogenic sources

| Sound | Source level (dB re 1 µPa-m) * | Bandwidth (Hz) | Major amplitude (Hz) | Duration (ms) | Directionality | Sound type |
|---|---|---|---|---|---|---|
| TNT (1-100 lbs) | 272–287 Peak | 2–1000 | 6–21 | ~ 1–10 | Omnidirectional | Tonal/ impulsive |
| Pile driving | 228 Peak/ 243–257 P-to-P | 20–>20 000 | 100–500 | 50 | Omnidirectional | Tonal/ impulsive |
| Offshore industrial activities | | | | | | |
| Dredging | 168–186 rms | 30–>20 000 | 100 - 500 | Continuous | Omnidirectional | Continuous |
| Drilling | 145–190 rms** | 10–10 000 | < 100 | Continuous | Omnidirectional | Continuous |
| Wind turbine | 142 rms | 16–20 000 | 30 - 200 | Continuous | Omnidirectional | |
| Shipping | | | | | | |
| Small boats and ships | 160 –180 rms | 20–>10 000 | >1 000 | Continuous | Omnidirectional | Continuous |
| Large vessels | 180–190 rms | 6–>30 000 | >200 | Continuous | Omnidirectional | Continuous |
| Sonar | | | | | | |
| Military sonar low- frequency | 215 Peak | 100 –500 | – | 600–1 000 | Horizontally focused | Tonal/ impulsive |
| Military sonar mid-frequency | 223–235 Peak | 2800–8200 | 3 500 | 500–2 000 | Horizontally focused | Tonal/ impulsive |
| Echosounders | 235 Peak | Variable | Variable 1500 – 36 000 | 5–10 ms | Vertically focused | Tonal/ impulsive |
| Seismic surveys | | | | | | |
| Airgun array | 260–262 P-to-P | 10–100 000 | 10–120 | 30–60 | Vertically focused* | Tonal/ impulsive |
| Other activities | | | | | | |
| Acoustic deterrent/harassment Devices | 132–200 Peak | 5 000–30 000 | 5 000–30 000 | Variable 15–500 ms | Omnidirectional | Tonal/ impulsive |
| Tidal and wave energy devices*** | 165–175 rms*** | 10–50 000 | – | Continuous | Omnidirectional | Continuous |

* Nominal source, ** Higher source levels from drill ships use of bow thrusters, *** Projection based on literature data with levels back-calculated at 1 m (Modified from Götz, 2009).

**Acoustic properties of some anthropogenic noises**

Sole, M. [et al.]. Marine invertebrates and noise. "Frontiers in marine science", 7 Març 2023, vol. 10.
URI: http://hdl.handle.net/2117/385081
DOI: 10.3389/fmars.2023.1129057

# Marine noise pollution

## Effects of noise on marine invertebrates (Early life stages)

- **Delayed hatching and development** - crustaceans eggs, **Impaired embryonic development** or significantly increase **larvae abnormality and mortality rates** in crustaceans, bivalve and gastropod (Christian et al., 2003; Courtenay et al., 2009; Stanley et al., 2010; Aguilar et al., 2013; Nedelec et al., 2014)

- Zooplankton (copepods, krill), *in situ* experiment on seismic air gun impacts on *Calanus* spp. - mortality (Fields et al., 2019; McCauley et al. (2017)

- **Critical period of increased sensitivity** to acoustic trauma in three species of cephalopod hatchlings *(Sepia officinalis, Loligo vulgaris* and *Illex coindetii*). Analysis of **noise damaged sensory epithelia - statocyst and lateral line system** (Solé et al., 2018)

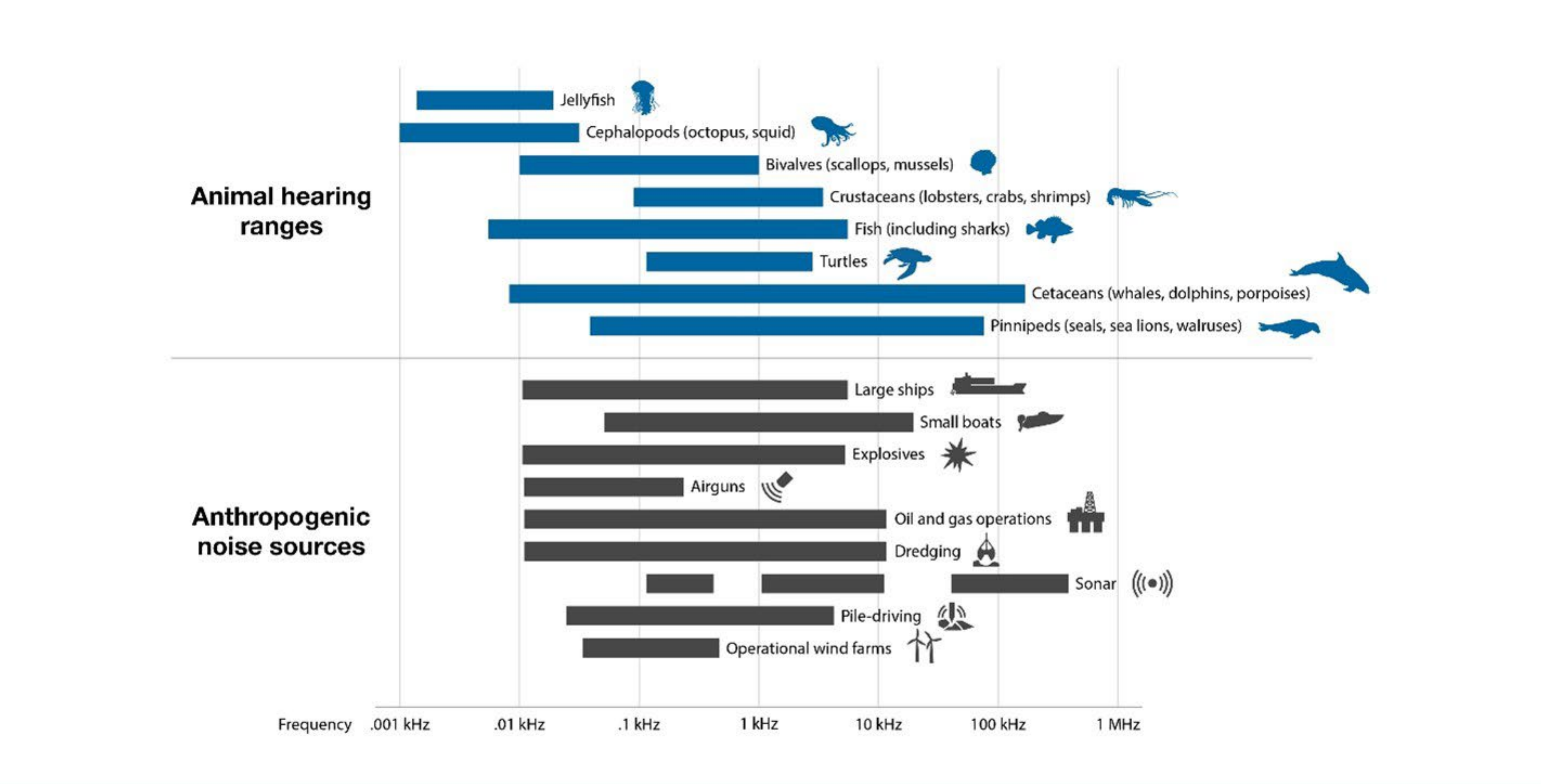
- Barnacles. **Primary settlement** of young cypris stages fails when exposed to low-frequency noise. Continuous ultrasound on their larvae - **delays in metamorphosis (**Branscomb & Rittschof, 1984; Guo et al., 2012; Choi et al., 2013)

- Mussel larvae - low-frequency sounds **to select the natural habitat** (Jolivet et al., 2016). Free-swimming larval stage - biotic sounds for **orientation, habitat selection and settlement** (Jeffs et al., 2003; Montgomery et al., 2006; Lillis et al., 2013).

Sole, M. [et al.]. Marine invertebrates and noise. "Frontiers in marine science", 7. 2023, vol. 10. URI: http://hdl.handle.net/2117/385081 DOI: 10.3389/fmars.2023.1129057

# Marine noise pollution

## Effects of noise on marine invertebrates (Adults) - Masking




https://www.dfo-mpo.gc.ca/oceans/noise-bruit/about-a-propos/index-eng.html

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# Marine noise pollution

## Acoustic sensitivity

| Species | Common name | Acoustic Perception | Method | Study |
|---|---|---|---|---|
| Bivalves | | | | |
| *Donax variabilis* | coquina | Sounds below 4096 Hz | Burrowing behaviour responses to sound | (Ellers, 1995) |
| *Macoma balthica* | Baltic clam | | Digging movements after vibratory stimulation | (Mosher, 1972) |
| *Mytilus edulis* | blue mussel | Vibration stimulus (Sinusoidal excitation -tonal signals (5–410 Hz). Thresholds 0.06–0.55 $m/s^2$ (RMS) | Behavioural changes (valve closure) | (Roberts et al., 2015) |
| *Crassostrea gigas* | Japanese oyster | 10–200 Hz pure tones | Valve closure (accelerometer oyster shell) | (Charifi et al., 2017) |
| *Mizuhopecten yessoensis* | Japanese scallop | 30–1000 Hz | Behavioural (shell oscillations) directional sensitivity of ASO to water-borne vibrations. | (Zhadan, 2005) |
| *Chlamys swifti* | swifti scallop | 30–1000 Hz | Behavioural (shell oscillations) directional sensitivity of ASO to water-borne vibrations. | (Zhadan, 2005) |
| *Patinopecten yessoensis* | Ezo giant scallop | ASO Fibres I: 20–1000 Hz (max 250–300 Hz)<br>ASO Fibres II: 20–340 Hz | Electrophysiological study ASO | (Zhadan and Semen'kov, 1984) |
| Cephalopods | | | | |
| *Sepia officinalis* | European common cuttlefish | Particle motion (acceleration) $<4x\ 10^{-3}\ m/s^2$ | Behavioural changes in breathing and jetting activity | (Packard et al., 1990 |
| *Sepia officinalis* | European common cuttlefish | Fit the frequency dependence of particle motion sensitivity model | Physical model of the sensory system | (Kaifu et al., 2011) |
| *Sepia officinalis* | European common cuttlefish | PM encompass the whole body of cephalopods and cause it to move with same phase and amplitude | Experimental set based on laser Doppler vibrometer techniques | (André et al., 2016) |
| *Sepioteuthis lessoniana* | oval squid | 400–1500 Hz | Auditory brainstem response (ABR) approach | (Hu et al., 2009) |
| *Octopus vulgaris* | common octopus | 400–1000 Hz | Auditory brainstem response (ABR) approach | (Hu et al., 2009) |
| *Octopus vulgaris* | common octopus | Fit the frequency dependence of particle motion sensitivity model | Physical model of the sensory system | (Kaifu et al., 2011) |
| *Octopus vulgaris* | common octopus | Particle motion (acceleration) $<4x\ 10^{-3}\ m/s^2$ | Behavioural changes in breathing and jetting activity | (Packard et al., 1990) |
| *Amphioctopus fangsiao/ Octopus ocellatus*[1] | *webfoot octopus* | 50–150 Hz | Behavioural changes (respiratory activities) | (Kaifu et al., 2007) |
| *Amphioctopus fangsiao/ Octopus ocellatus*[1] | *webfoot octopus* | 141 Hz particle motion at particle accelerations below 1.3 × 10 -3 $m/s^2$ | Behavioural changes (respiratory activities) | (Kaifu et al., 2008) |
| *Amphioctopus fangsiao/ Octopus ocellatus*[1] | *webfoot octopus* | Fit the frequency dependence of particle motion sensitivity model | Physical model of the sensory system | (Kaifu et al., 2011) |
| *Loligo vulgaris* | European squid | Particle motion (acceleration) $<4x\ 10^{-3}\ m/s^2$ | Behavioural changes in breathing and jetting activity | (Packard et al., 1990) |
| *Loligo pealeii* | longfin squid | 30–500 Hz (lowest thresholds between 100–200 Hz) | Auditory evoked potentials (AEPs) with electrodes placed near the statocysts | (Mooney et al., 2010) |

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# Marine noise pollution

## Acoustic sensitivity

| | |
|---|---|
| **Bivalves** | **10 – 1000Hz** |
| **Cephalopods** | **400 – 1500 Hz** |
| **Crustaceans** | **20 – 3000 Hz** |

| Crustaceans | | | | |
|---|---|---|---|---|
| *Palaemon serratus* | *common* prawn | 100–3000 Hz | Anatomical techniques, electron microscopy and electrophysiology | (Lovell et al., 2005) (Lovell et al., 2006) |
| *Neprhops norvegicus* | Norway lobster | 20–180 Hz | Behaviour responses to | (Goodall et al., 1990) |
| | | | | (Roberts et al., 2016) |
| | | | | (Hughes et al., 2014) |
| | | | | (Tautz & Sandeman, 1980) |
| *Ovalipes catharus* | paddle crabs | 100–200 Hz | auditory evoked potentials (AEP) | (Radford et al., 2016) |
| *Homarus americanus* | American lobster | 20–300 Hz | Electrophysiological recordings (Sensory hairs, cuticular sensilla) | (Derby, 1982) |
| *Uca* sp. *Ocypode* sp. | fiddler crab ghost crab | ≥300 Hz | Barth's myochordotonal organs (Barth's MCO) | (Popper et al., 2001) |
| *Alpheus richardsoni* | snapping shrimp | ≥1500 Hz. (more sensitive: 80–100 Hz) | Electrophysiological, auditory evoked potential (AEP) in response to only particle motion and to both particle motion and sound pressure. | (Dinh & Radford, 2021) |

([1]*Octopus ocellatus* has been accounted as a junior synonym of *Amphioctopus fangsiao* (Norman and Hochberg, 2005).

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# Marine noise pollution

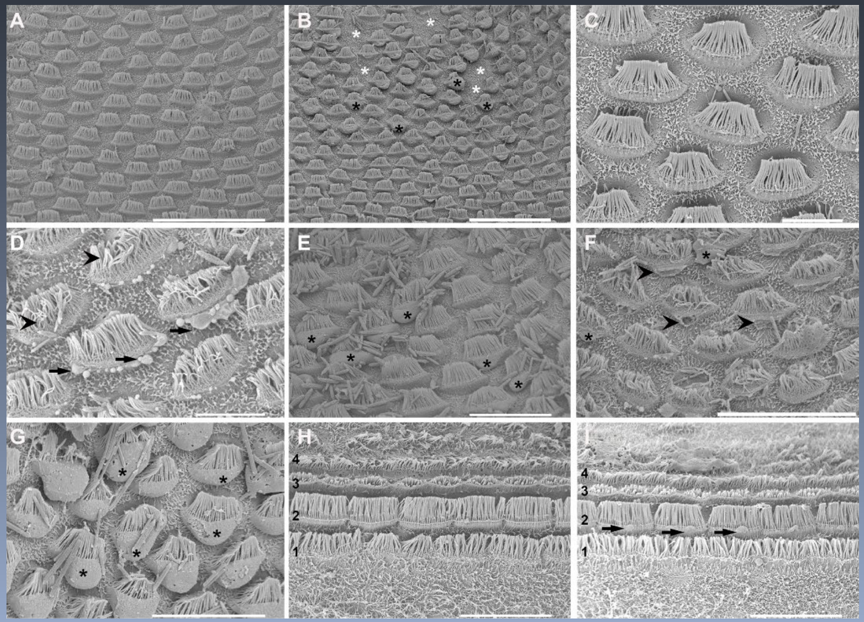
## Effects of noise on marine invertebrates (Adults)- Physical effects

**Bivalves**
- Dose-dependent increase scallop **mortality** - exposure to an airgun (Day et al., 2016).
- Abnormal reflexes, indicating **damage to mechanosensory organs** (Day et al., 2017

**Cephalopods**
- Giant squid stranding (Guerra et al., 2004)
- Consequences on the **functionality and physiology of cephalopod statocysts**, sensory organs responsible for equilibrium and movements in the water column (André et al., 2011; Solé et al., 2013a; Solé et al., 2013b; Solé et al., 2017) (laboratory and offshore conditions) (feeding and mating cancellation and irregular swimming). Lesions on the exposed animals consistent with a **massive acoustic trauma** observed in vertebrate species.

**Cnidarians** and **ctenophores (**both in the polyp and the medusa stage)
- Sensory organs in their tentacles (detect vibration in water -prey moviment, changes in their surrounding environament- **Morphological effects (severe damages to the statocyst sensory epithelia)** after noise exposure (*Cotylorhiza tuberculata* and *Rhizostoma pulmó)* (Solé et al., 2016)

**Crustaceans**
- Blue crabs (*Callinectes sapidus*) increased **mortality -** underwater explosions (Moriyasu et al., 2004)
- **Sub-lethal effects** of continuous, low-frequency anthropogenic noise - Decapoda (Edmonds et al., 2016)
- Airgun exposure - **ultrastructural statocyst damages** in rock lobsters up to a year later (Day et al., 2016). **Impaired righting** and significant damage to the sensory hairs of the statocyst (Day et al., 2019). Reflex impairment and statocyst damage persisted up to 365 days post-exposure – and did not improve following moulting.




Sole, M. [et al.]. Marine invertebrates and noise. "Frontiers in marine science", 7. 2023, vol. 10. URI: http://hdl.handle.net/2117/385081
DOI: 10.3389/fmars.2023.1129057

# Marine noise pollution

## Case Studies (Cephalopods). Capture and Husbandry

Catalan Coast (NW Mediterranean Sea)
2 years

Closed system of recirculating natural seawater at 2 plastic tanks of 2000L capacity (18-20ºC, salinity 35‰ and natural oxygen pressure)

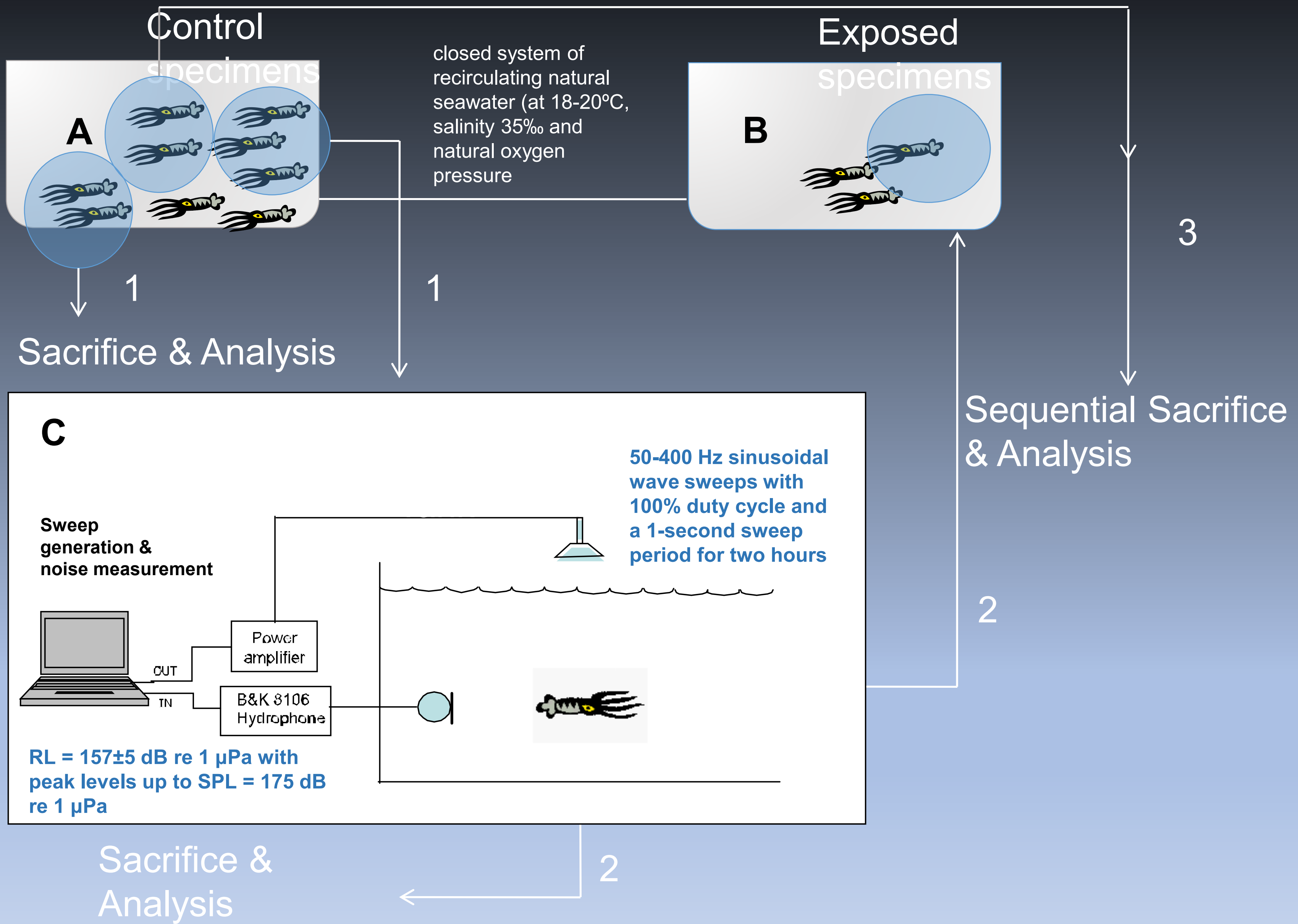

30 *Sepia officinalis*

To analyse adaptation to captivity.

Analysis (LM, SEM & TEM) of their inner sensory statocyst epithelium

# Marine noise pollution

## Case Studies (Cephalopods)
## Sound exposure protocol

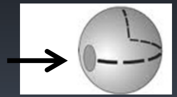


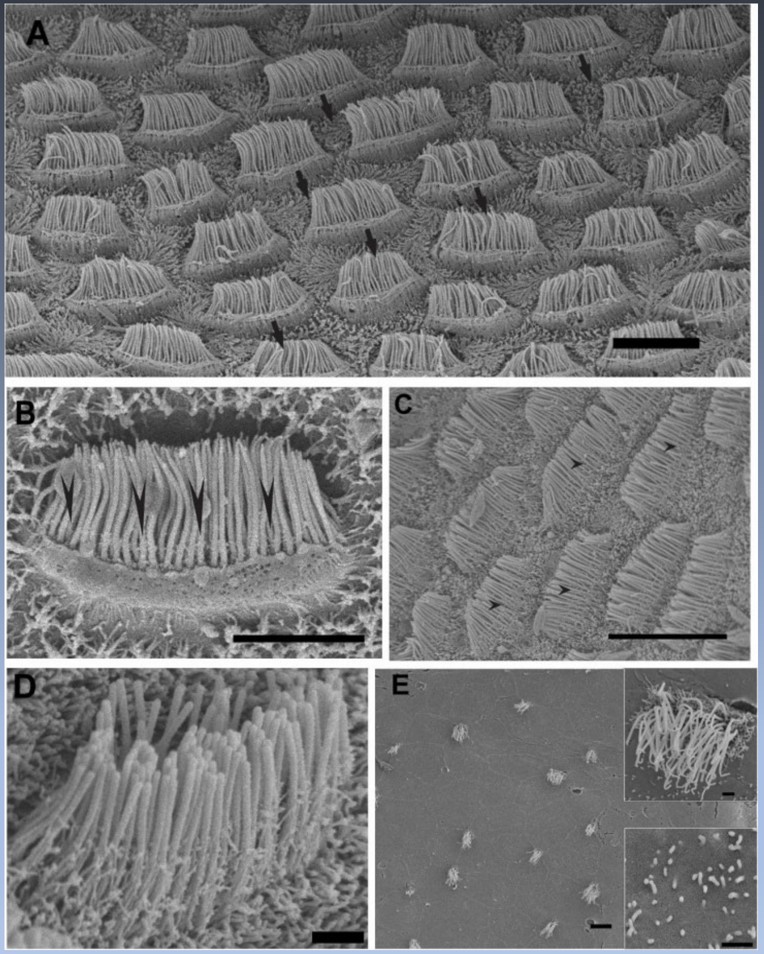
# Marine noise pollution

## Case Studies (Cephalopods)

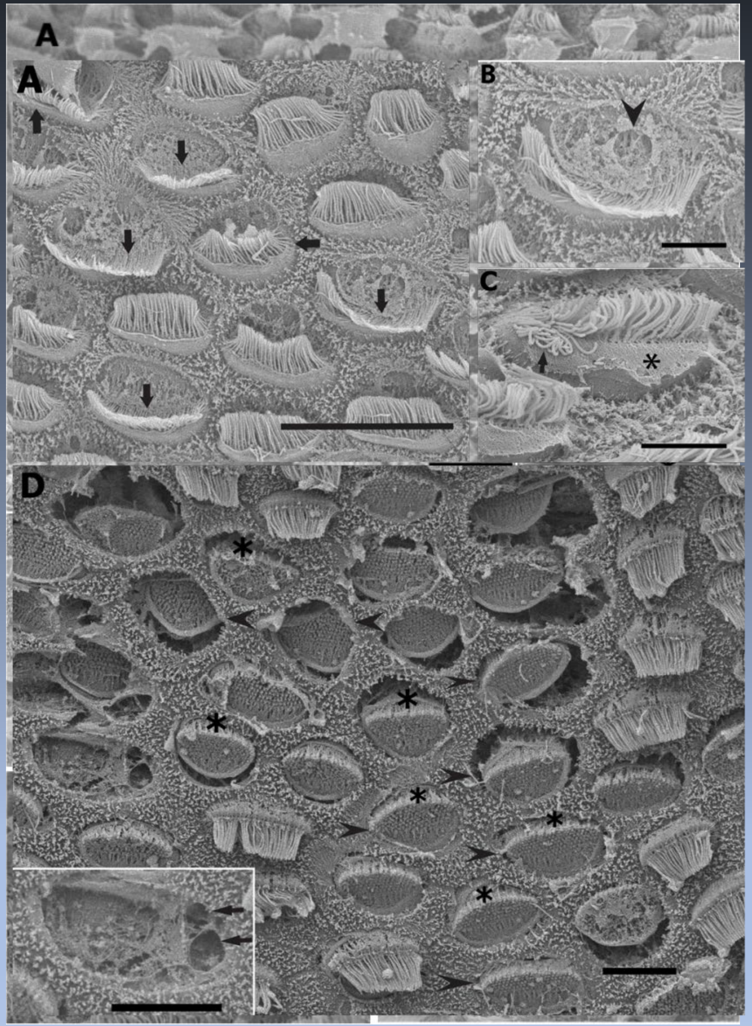
### Analysis (SEM & TEM) of statocyst inner sensory epithelium

### Macula statica princeps






**SEM. Control** ***Sepia officinalis (A & B); Octopus vulgaris (C & D) macula*** **statica princeps;** ***Octopus vulgaris*** **inner sac statocyst morphology (E)**




**SEM.** ***Sepia officinalis*** **msp, presents different levels of lesions. A-C: sacrificed immediately after sound exposure. D: sacrificed 48h after sound exposure.**

SEM. *Sepia officinalis* (A, B, E) and *Octopus vulgaris* (C, D) *msp*, A-D: sacrificed 48h after sound exposure. E: sacrificed 72h after sound exposure


Solé, M., Lenoir, M., Durfort, M., López-Bejar, M., Lombarte, A., and André, M. (2013a). Ultrastructural damage of Loligo vulgaris and Illex coindetii statocysts after low frequency sound exposure. PloS One 8 (10), 1–12. doi: 10.1371/journal.pone.0078825

Solé, M., Lenoir, M., Durfort, M., López-Bejar, M., Lombarte, A., van der Schaar, M., et al. (2013b). Does exposure to noise from human activities compromise sensory information from cephalopod statocysts? Deep-Sea Res. Part II: Topical Stud. Oceanography 95, 160–181. doi: 10.1016/j.dsr2.2012.10.006

André, M. , Solé, M. et al. Low-frequency sounds induce acoustic trauma in cephalopods. Front. Ecol. Environ. 9, 489–493 (2011).

# Marine noise pollution

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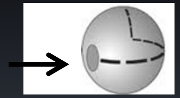
## Case Studies (Cephalopods)

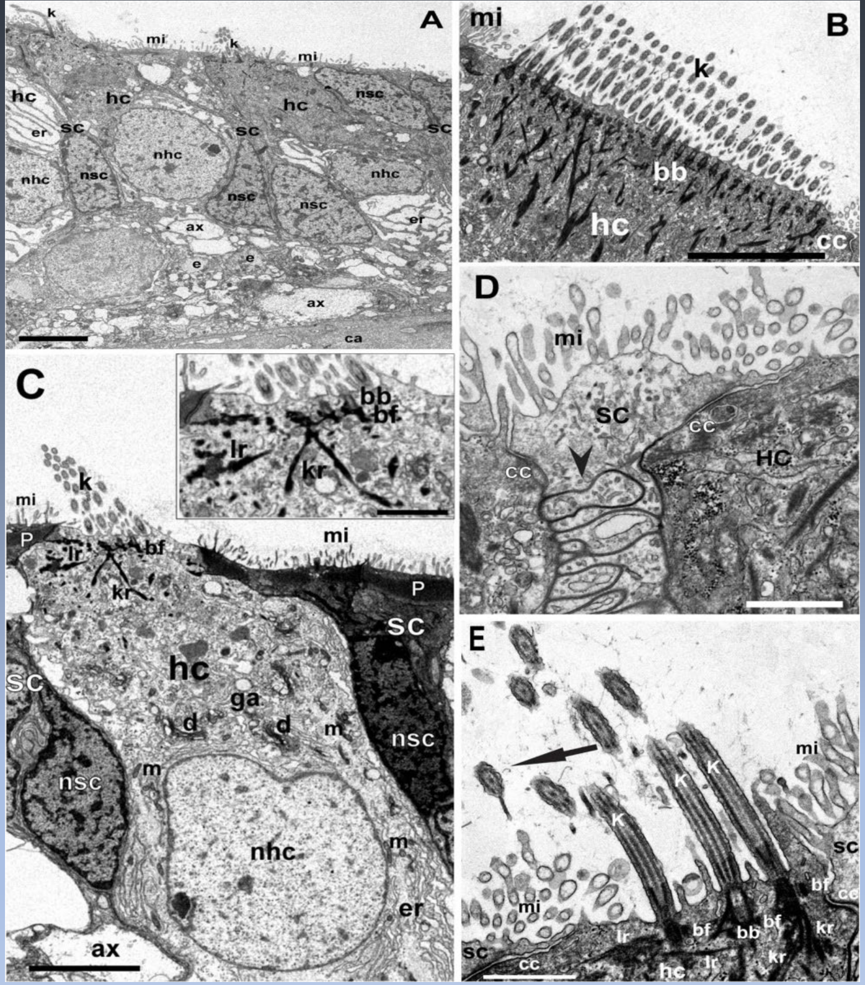
## Analysis (SEM & TEM) of statocyst inner sensory epithelium

## Macula statica princeps

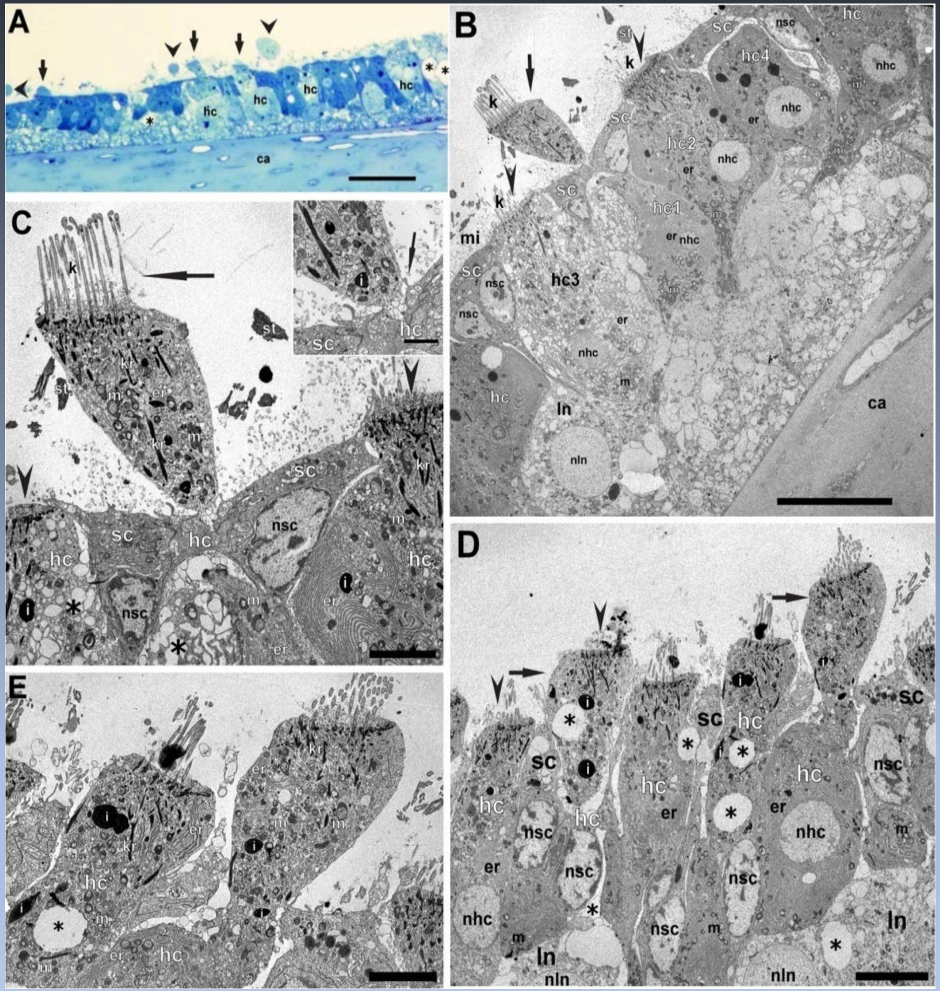


Solé, M., Lenoir, M., Durfort, M., López-Bejar, M., Lombarte, A., and André, M. (2013a). Ultrastructural damage of Loligo vulgaris and Illex coindetii statocysts after low frequency sound exposure. PloS One 8 (10), 1–12. doi: 10.1371/journal.pone.0078825

Solé, M., Lenoir, M., Durfort, M., López-Bejar, M., Lombarte, A., van der Schaar, M., et al. (2013b). Does exposure to noise from human activities compromise sensory information from cephalopod statocysts? Deep-Sea Res. Part II: Topical Stud. Oceanography 95, 160–181. doi: 10.1016/j.dsr2.2012.10.006



**TEM. Cellular organization of control *Sepia officinalis* (A, C) and *Octopus vulgaris* (B, D, E) *msp***



**LM (A) and TEM (B-E). *Octopus vulgaris macula statica princeps (msp)*, from an individual sacrificed 48h after sound exposure.**

# Marine noise pollution

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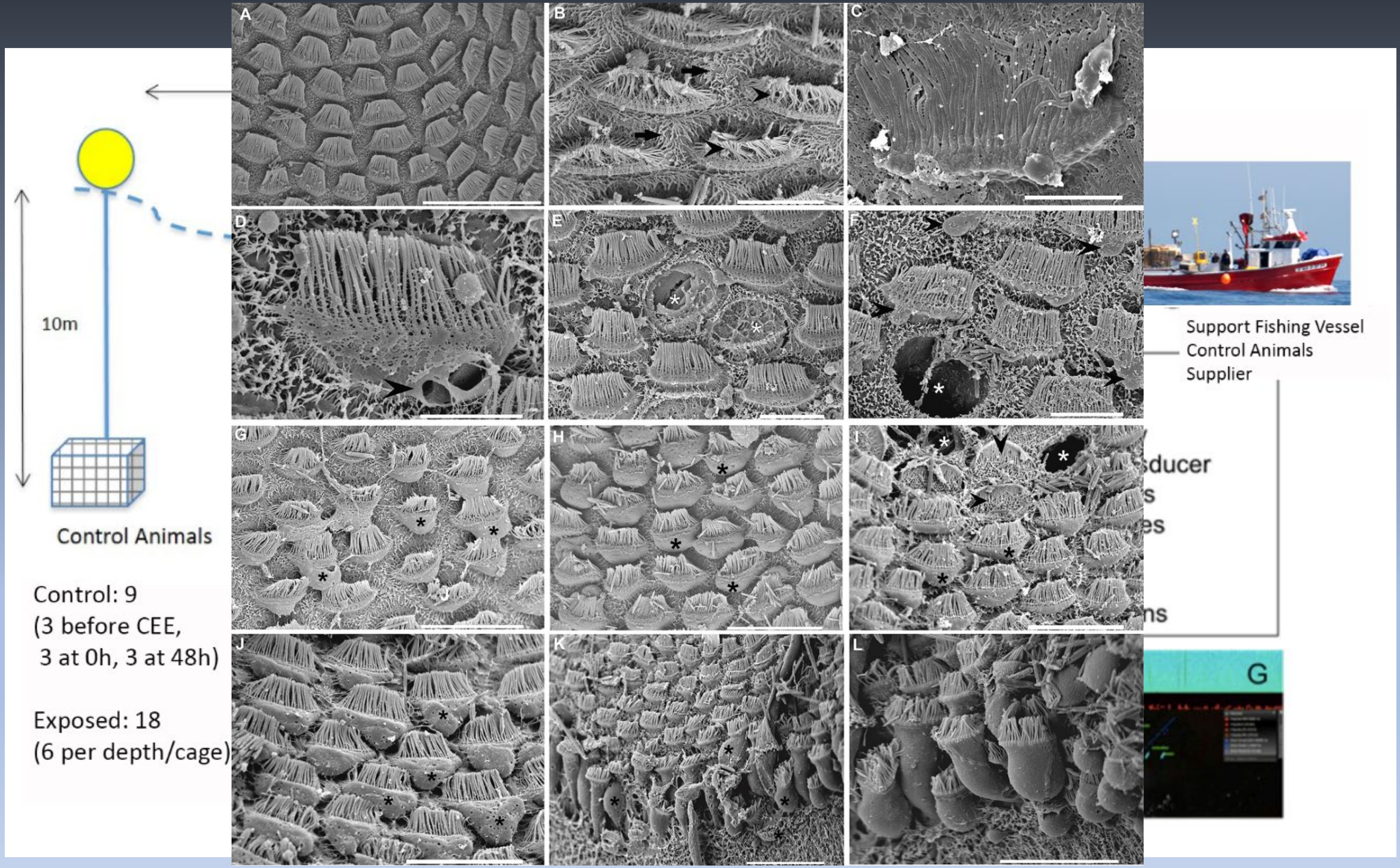
## Case Studies (Cephalopods - Offshore experiments)

## AQUO AT SEA CONTROLLED EXPOSURE EXPERIMENTS ON INVERTEBRATES




Solé, M., Sigray, P., Lenoir, M., van der Schaar, M., Lalander, E., and André, M. (2017). Offshore exposure experiments on cuttlefish indicate received sound pressure and particle motion levels associated with acoustic trauma. Sci. Rep. 7, 45899. doi: 10.1038/srep4589912

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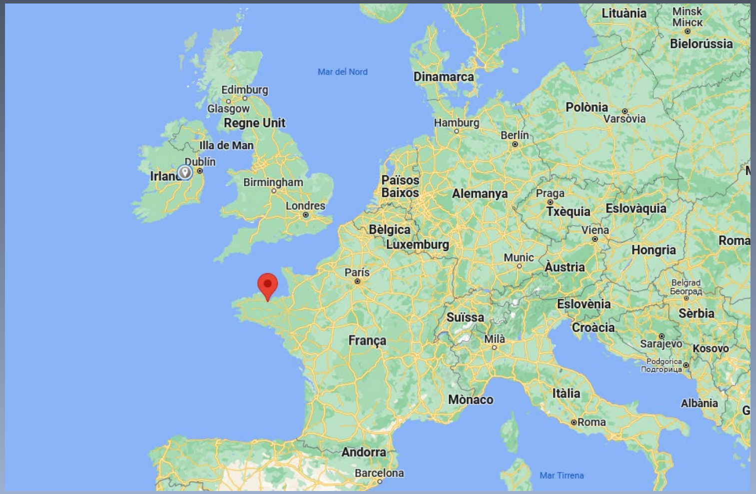
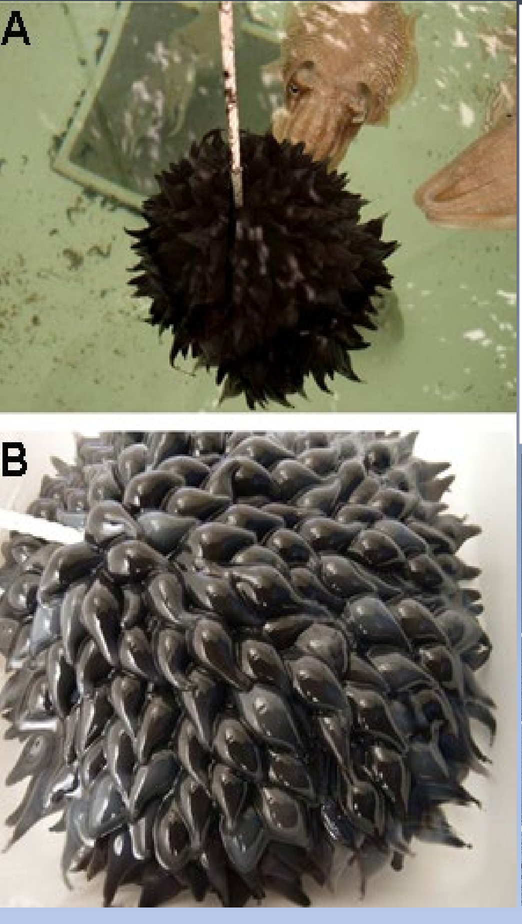
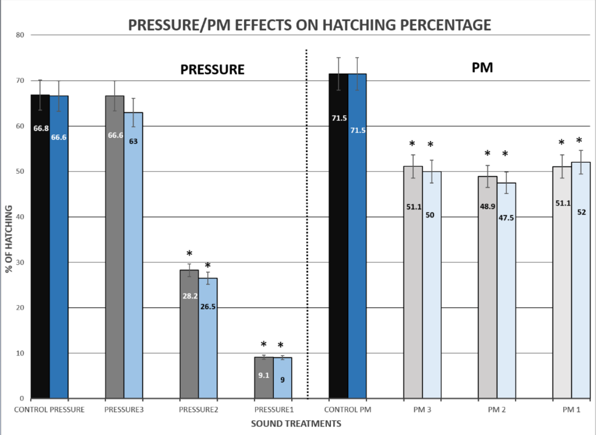
# Marine noise pollution - Applications -

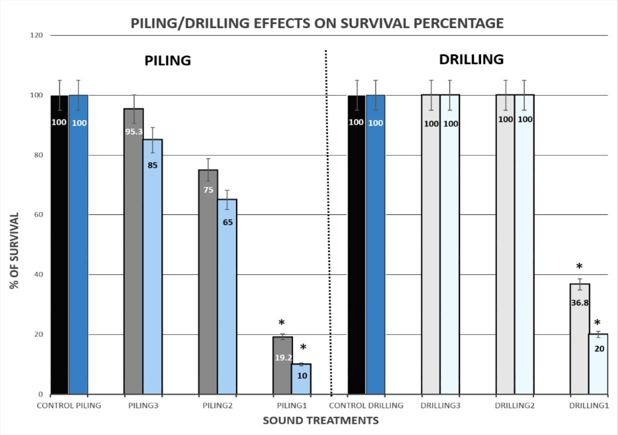
## Case Studies (Windmill construction - Noise influence on cuttlefish - St Brieuc Wind Farm Site)

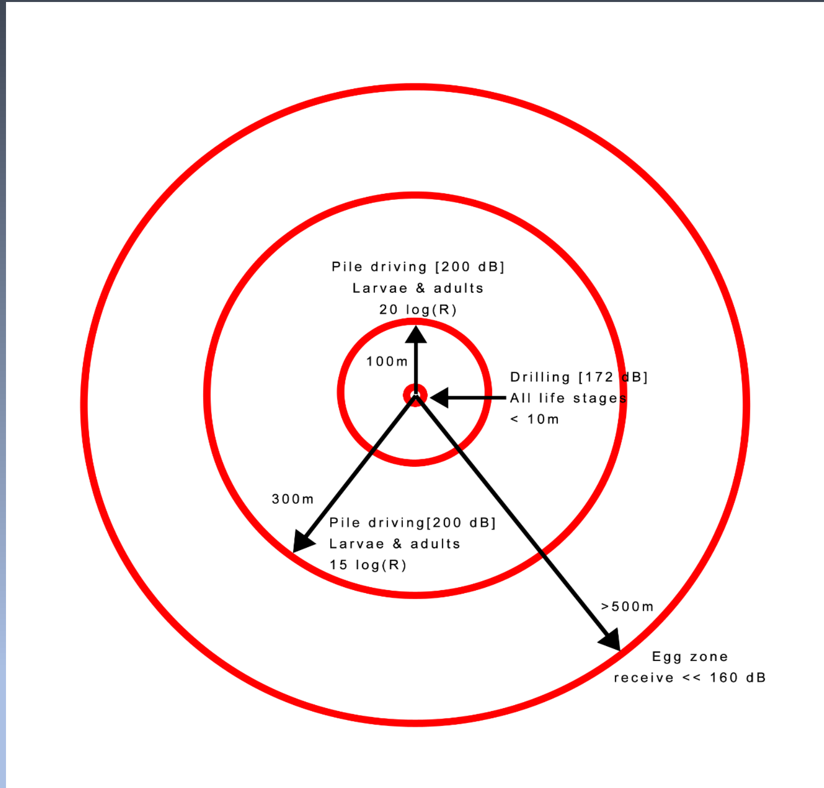


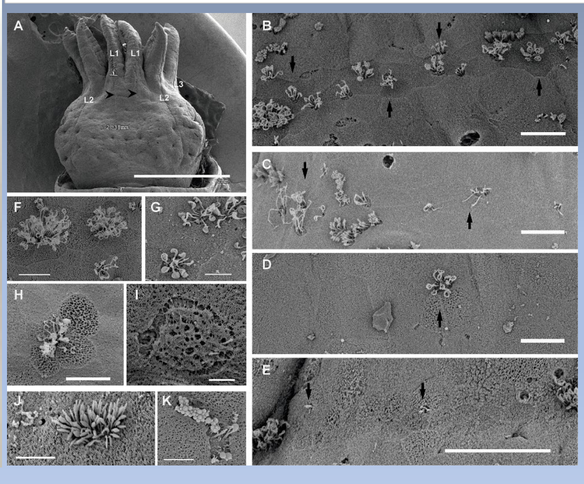

Solé , M., De Vreese, S., Fortuño, J.-M., van der Schaar, M., Sanchez, A., and André , M. (2022). Commercial cuttlefish exposed to noise from offshore windmill construction show short-range acoustic trauma. Environ. Pollut. 312, 119853. doi: 10.1016/j.envpol.2022.119853

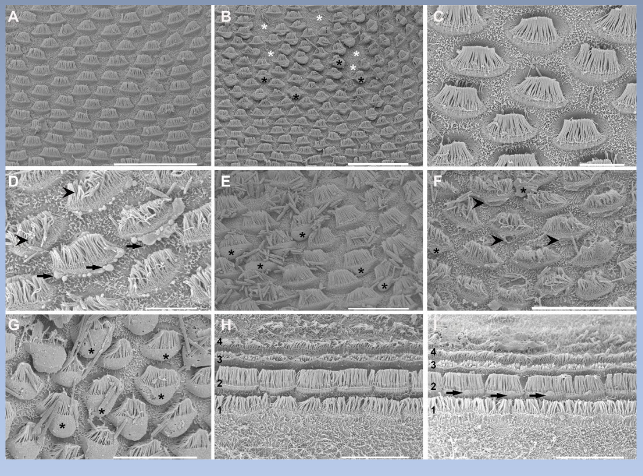





# Effects of windmill construction on *Sepia officinalis* (eggs, larva and adults)

**Ailes Marines SAS (Iberdrola Group). Project: Noise influence on cuttlefish invertebrate - St Brieuc Wind Farm Site (Ref. CPCS – 771596). France. 2018-2020**

SONSETC Making Sense of Sounds
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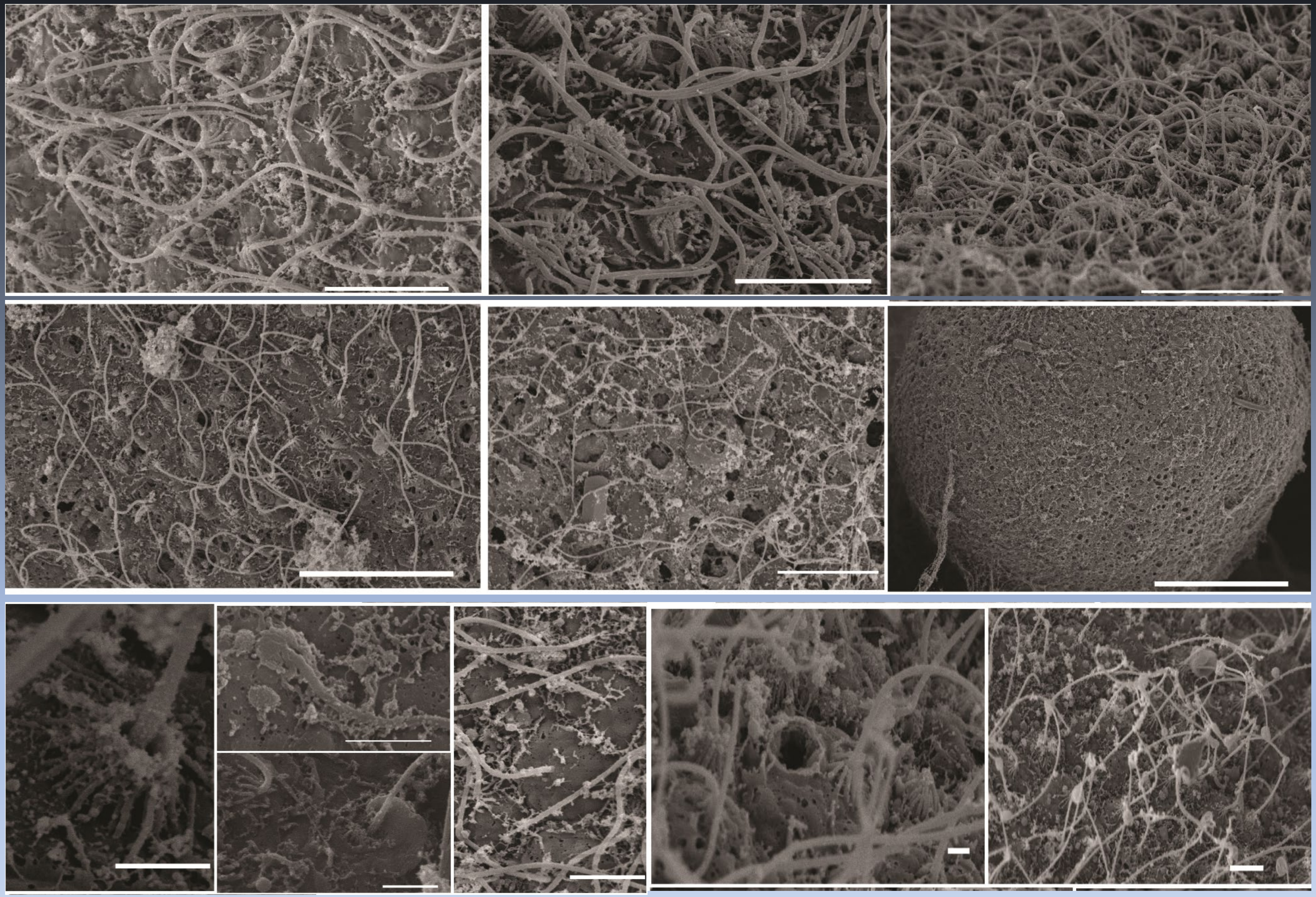
# Marine noise pollution

Case Studies
(Cnidarians)

*C. tuberculata*



Solé , M., Lenoir, M., Fontuño, J. M., Durfort, M., van der Schaar, M., and André, M. (2016). Evidence of cnidarians sensitivity to sound after exposure to low frequency noise underwater sources. Sci. Rep. 6, 37979. doi: 10.1038/srep37979

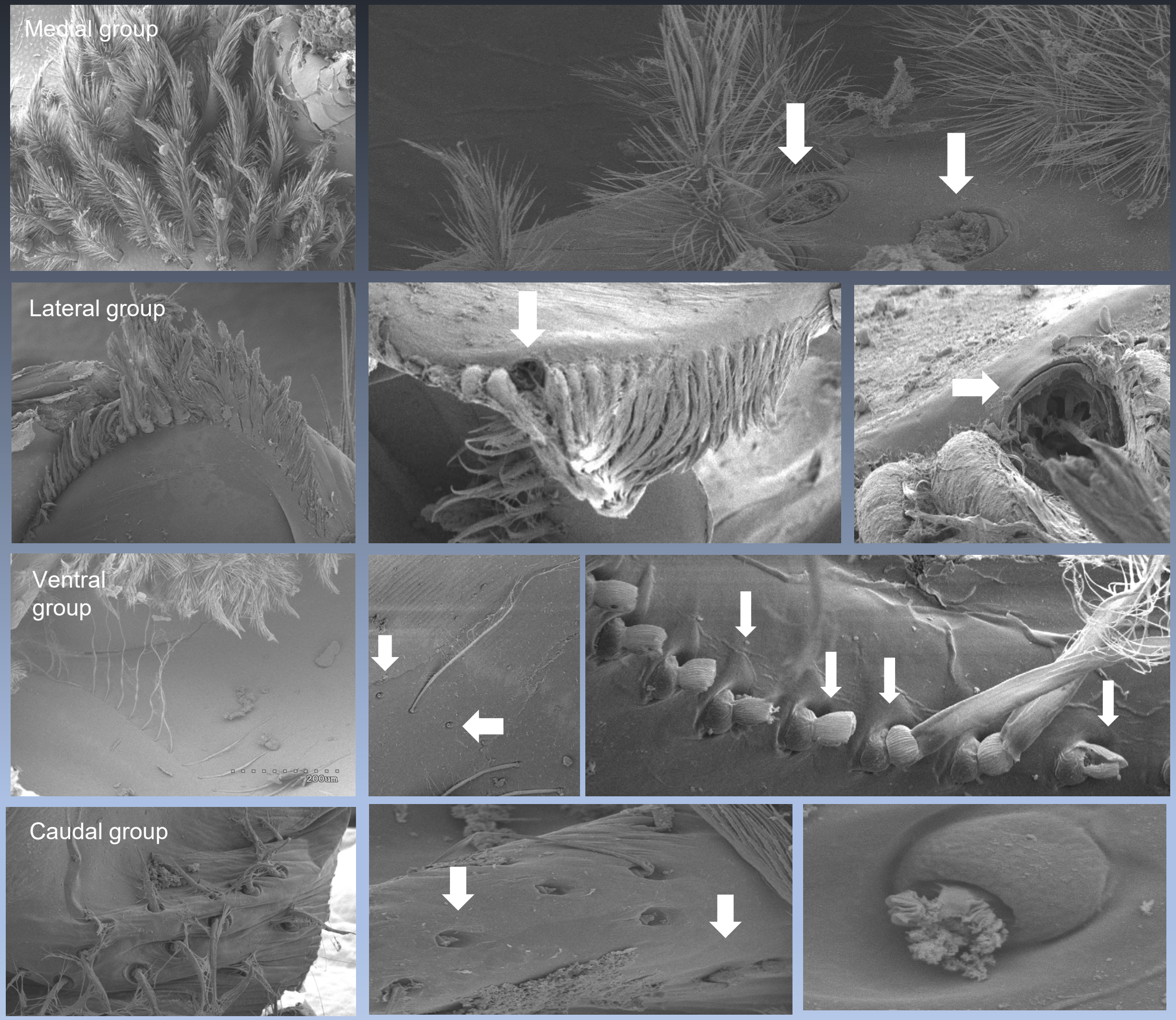
# Marine noise pollution

## Case Studies (hermit crab + anemone)

***Dardanus calidus***

**Lesions:**

- **Loss of hairs in the setae**
- **Setae partially or totally ejected from the sensory epithelium leaving holes**




Solé M, De Vreese S, Fortuño JM, van der Schaar M. Artificial sound impact could put at risk hermit crabs and their symbiont anemones. Sci Total Environ. 2023 Nov 20;900:165756. doi: 10.1016/j.scitotenv.2023.165756. Epub 2023 Jul 25. PMID: 37499834.

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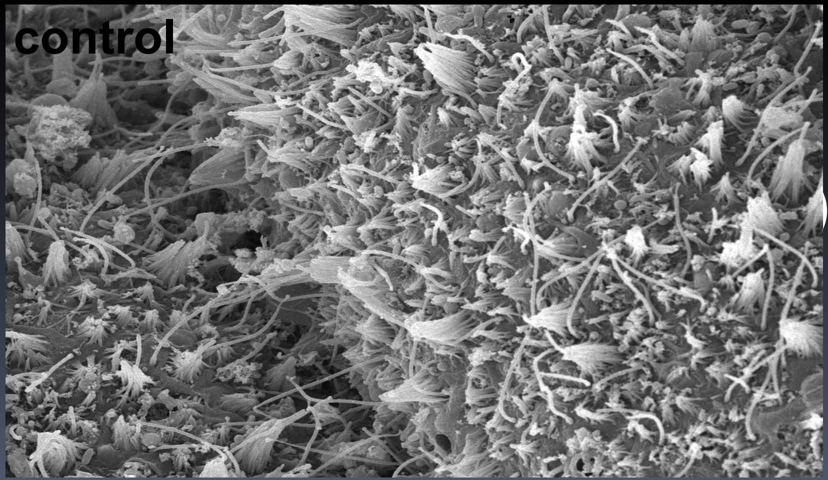
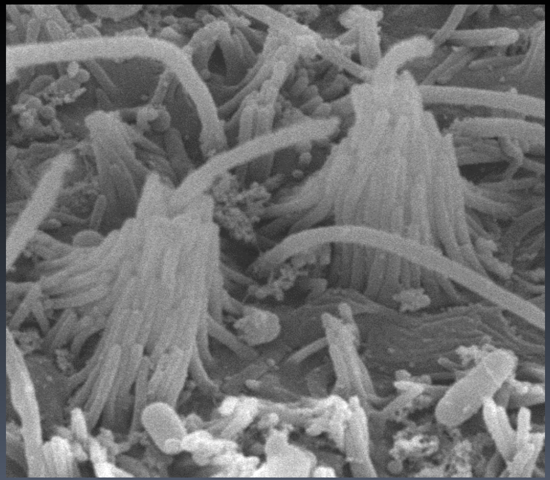
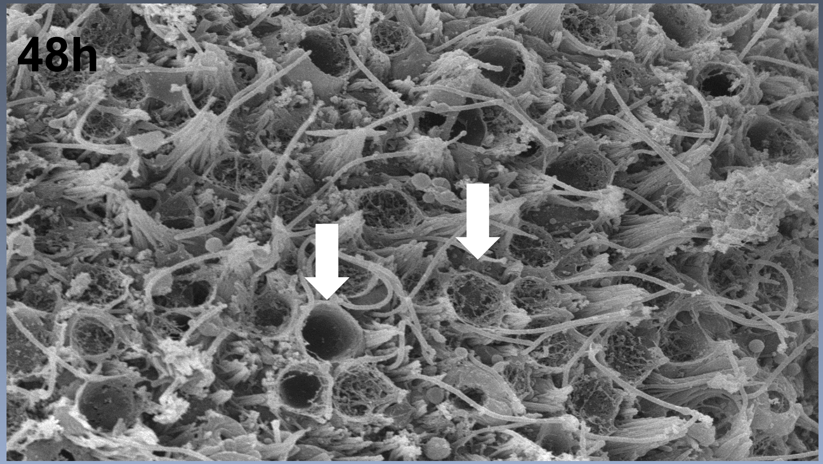
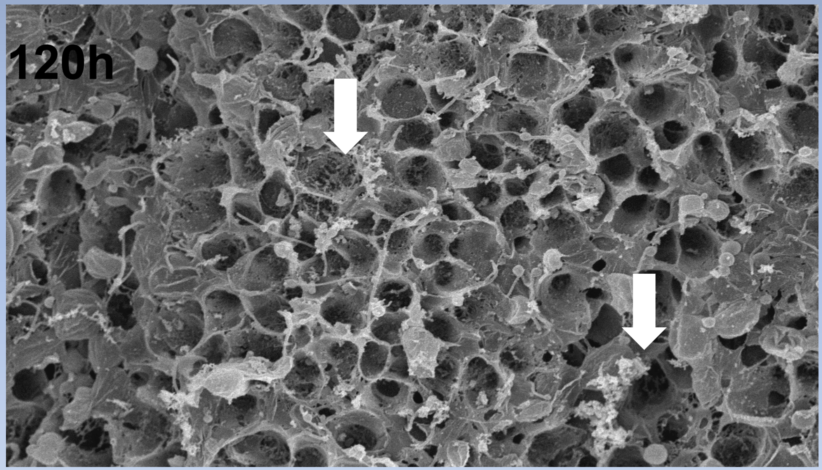
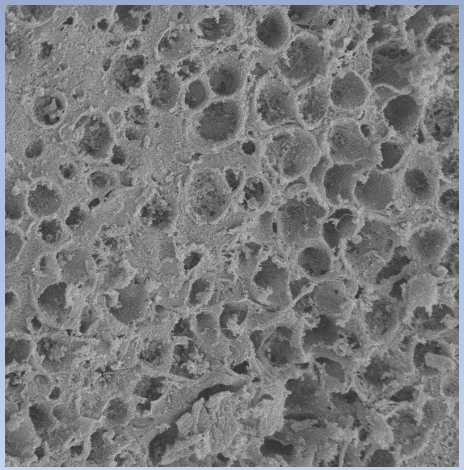




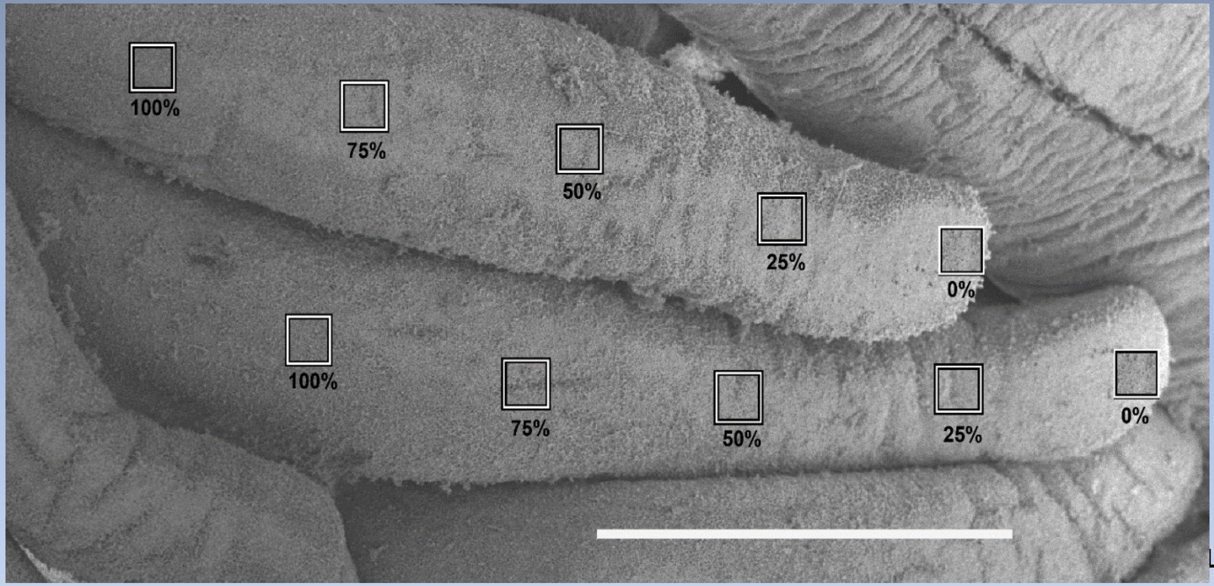



The lesions included:

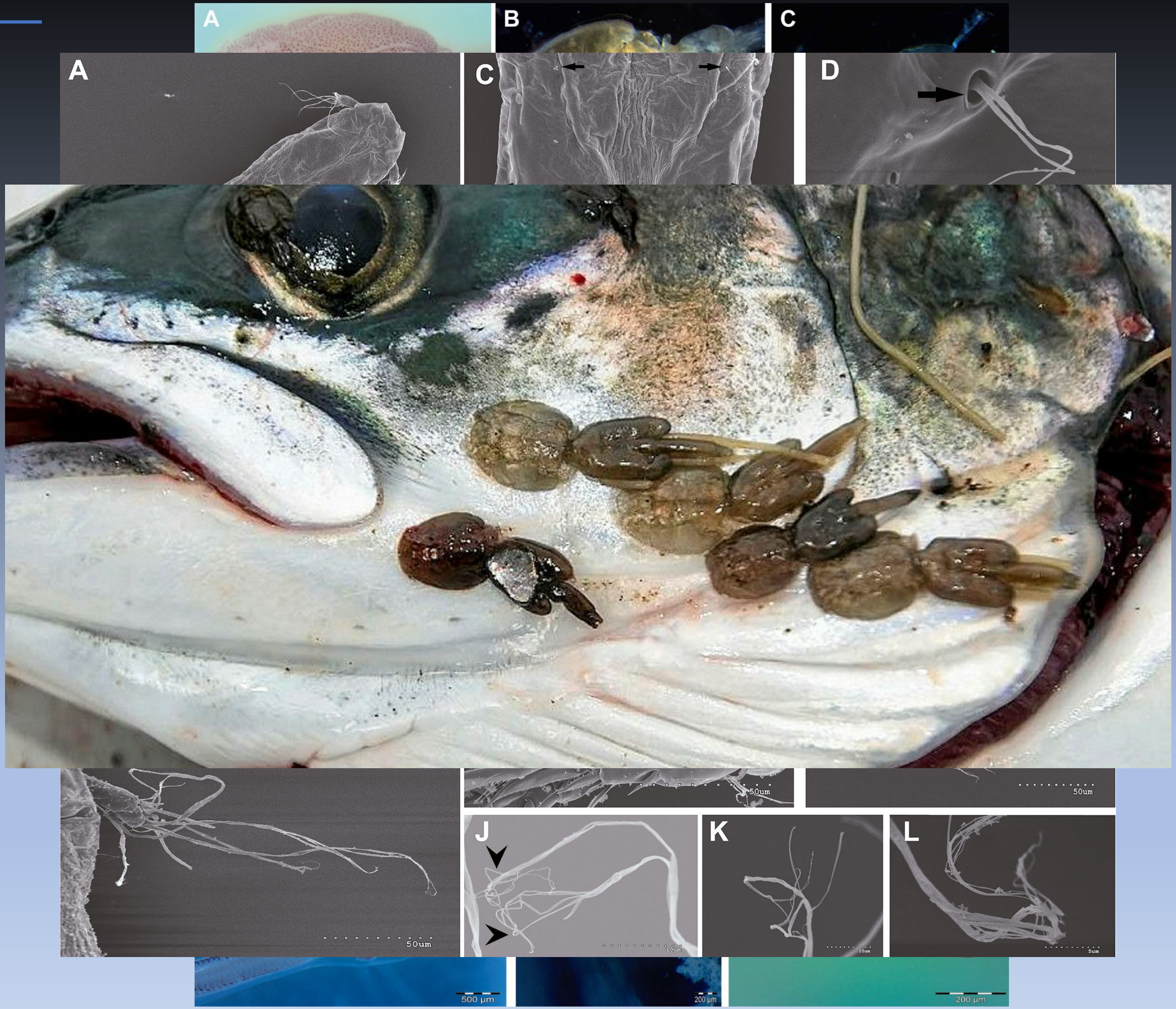
- Loss of the unique kinocilium
- Crown of stereocilia lost or totally fused
- Bent, flaccid or expoiled microvilli
- Hair cells partially or totally ejected from the sensory epithelium leaving holes

***Calliactis parasitica***



# Fight against pests

**Case Studies (BIOACOUSTIC APPLICATIONS to mitigate the effects of aquatic plagues)**




**Sea lice (*Lepeophtheirus salmonis*) + Norwegian Salmon**

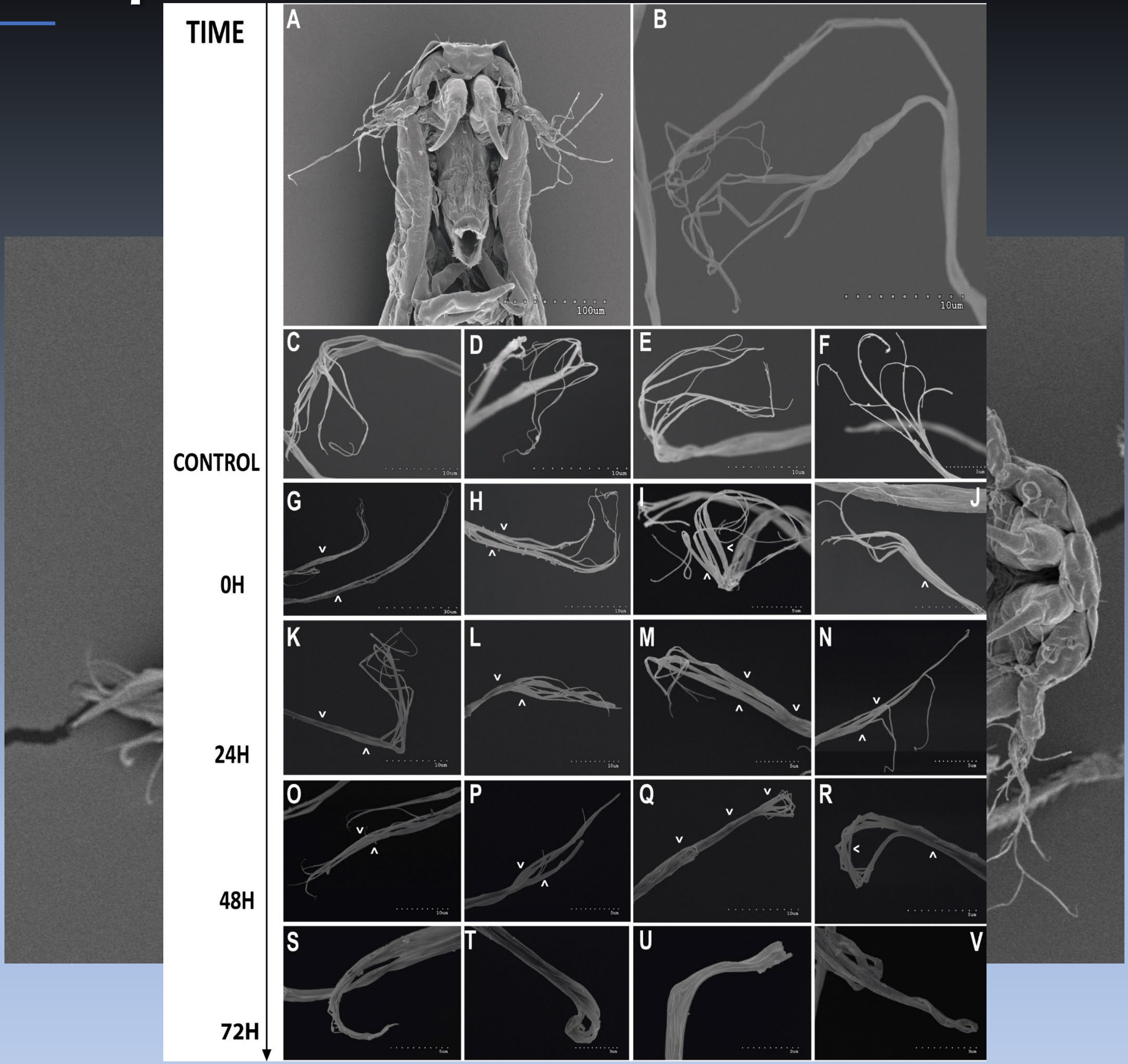
Solé , M., Lenoir, M., Fortuño, J. M., De Vreese, S., van der Schaar, M., and André , M. (2021b). Sea Lice are sensitive to low frequency sounds. J. Mar. Sci. Eng. 9 (7), 765. doi: 10.3390/jmse9070765

# Fight against pests

**Case Studies (BIOACOUSTIC APPLICATIONS to mitigate the effects of aquatic plagues)**

Patents:
André M., Solé M., Van der Schaar, De Vreese S (International Patent WO 2018/167003 A1). 20-09-2018. A method for inducing lethal lesions in sensory organs of undesirable aquatic organisms by use of sound. Licensed to SEASEL SOLUTIONS AS [NO/NO]; P.O.BOX 93 N-6282 BRATTVÅG (NO).

André M., Solé M., Van der Schaar (Norwegian patent WO/2020/048945). 03-09-2019. System and method for reducing sea lice exposure in marine fish farming. Licensed to SEASEL SOLUTIONS AS [NO/NO]; P.O.BOX 93 N-6282 BRATTVÅG (NO).



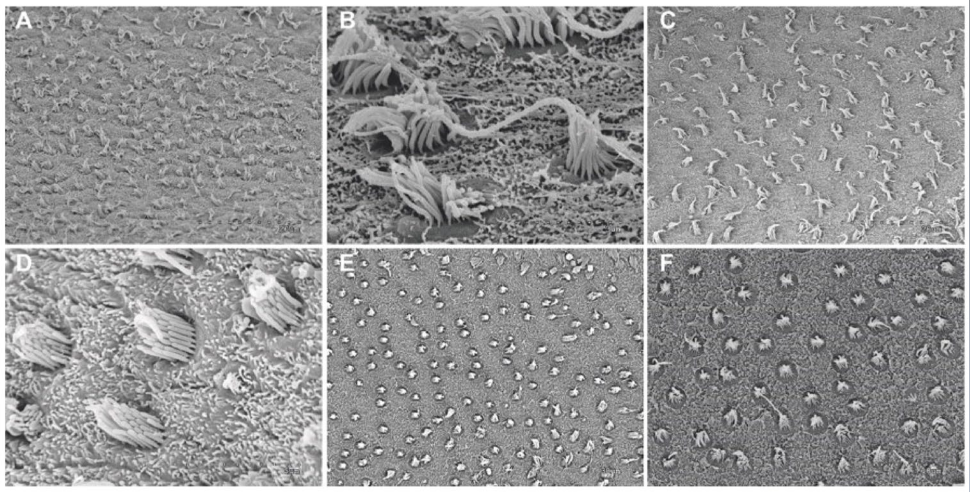

Solé , M., Lenoir, M., Fortuño, J. M., De Vreese, S., van der Schaar, M., and André , M. (2021b). Sea Lice are sensitive to low frequency sounds. J. Mar. Sci. Eng. 9 (7), 765. doi: 10.3390/jmse9070765

**Sea lice (*Lepeophtheirus salmonis*) + Norwegian Salmon**

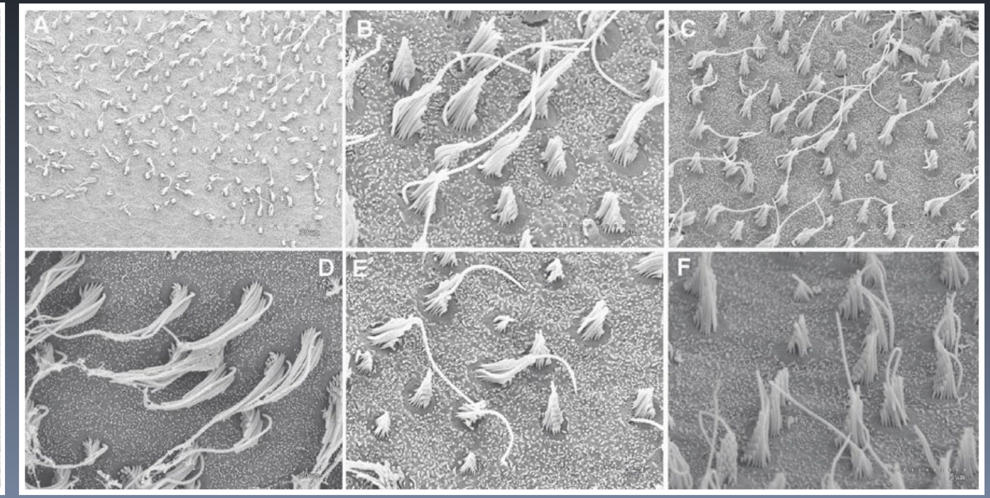
# Fight against pests



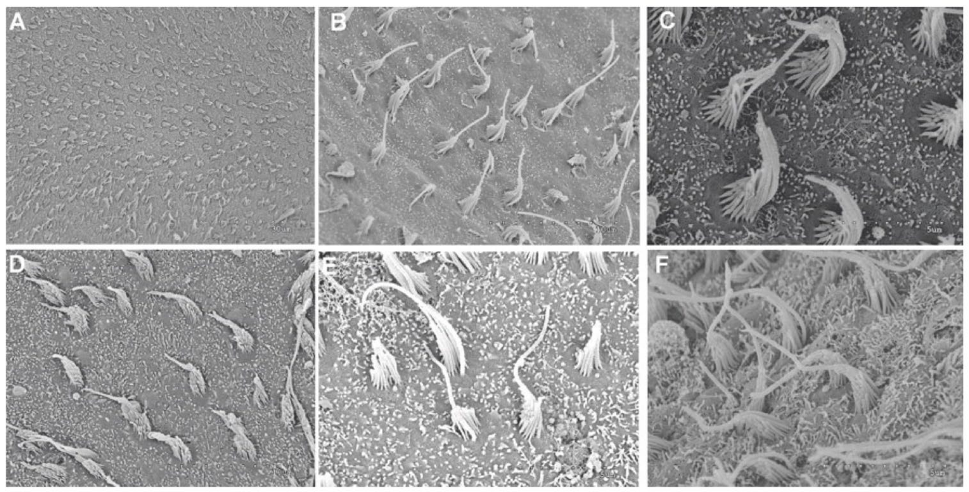
**Case Studies (BIOACOUSTIC APPLICATIONS to mitigate the effects of aquatic plagues)**




saccule




utricle




lagena

**Norwegian Salmon**

**Otholit organ**
**SEM assessment**

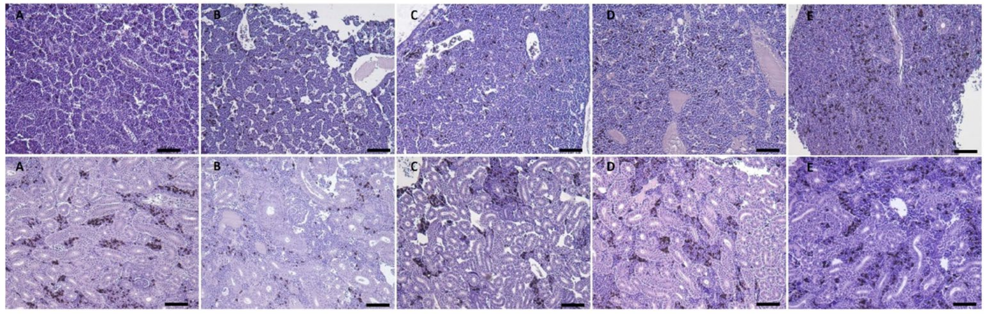
Solé, M.; Constenla, M.; Padrós, F.; Lombarte, A.; Fortuño, J.-M.; van der Schaar, M.; André, M. Farmed Salmon Show No Pathological Alterations When Exposed to Acoustic Treatment for Sea Lice Infestation. *J. Mar. Sci. Eng.* **2021**, *9*, 1114. https://doi.org/10.3390/jmse9101114

# Fight against pests

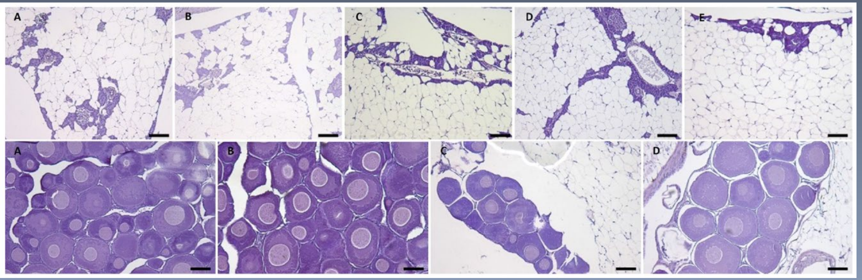
## Histological assessment

## Norwegian Salmon

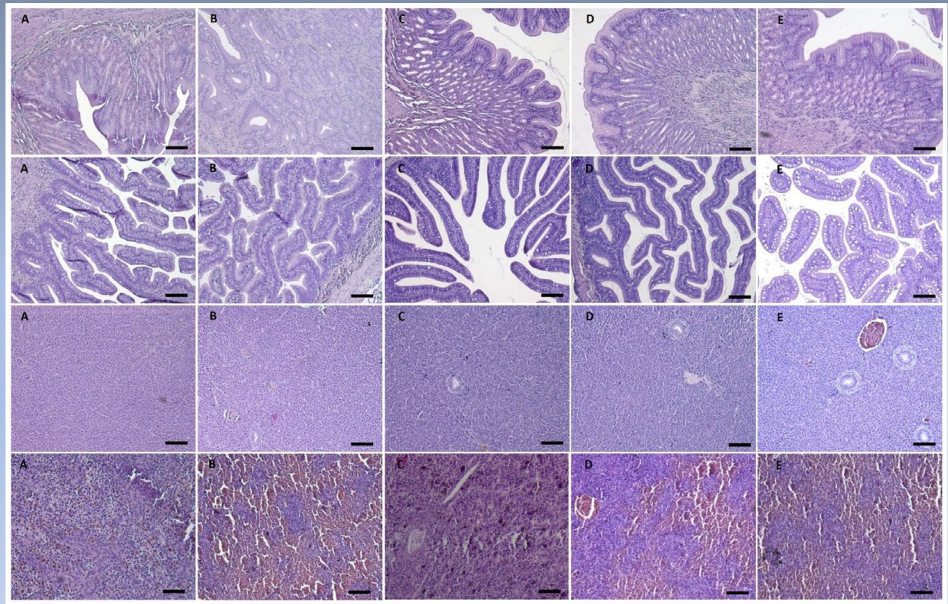
**Case Studies (BIOACOUSTIC APPLICATIONS to mitigate the effects of aquatic plagues)**



Head kidney (**first line**) and posterior kidney (**second line**) of salmon at different sampling times. (**A**) Control. (**B**) 1 week after exposure. (**C**) 2 weeks after exposure. (**D**) 3 weeks after exposure. (**E**) 4 weeks after exposure. Scale bar: 100 μm.



Pancreas and adipose tissue (visceral fat) (**first line**) and gonad (**second line**) of salmon at different sampling times. (**A**) Control. (**B**) 1 week after exposure. (**C**) 2 weeks after exposure. (**D**) 3 weeks after exposure. (**E**) 4 weeks after exposure. Scale bar: 100 μm.



Stomach (**first line**), intestine (**second line**), liver (**third line**) and spleen (**fourth line**) of salmon at different sampling times. (**A**) Control. (**B**) 1 week after exposure. (**C**) 2 weeks after exposure. (**D**) 3 weeks after exposure. (**E**) 4 weeks after exposure. Scale bar: 100 μm.

Solé, M.; Constenla, M.; Padrós, F.; Lombarte, A.; Fortuño, J.-M.; van der Schaar, M.; André, M. Farmed Salmon Show No Pathological Alterations When Exposed to Acoustic Treatment for Sea Lice Infestation. *J. Mar. Sci. Eng.* **2021**, *9*, 1114. https://doi.org/10.3390/jmse9101114

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# Marine noise pollution

## Effects of noise on marine invertebrates (Adults) - Behavioural effects

Sole, M. [et al.]. Marine invertebrates and noise. "Frontiers in marine science", 7. 2023, vol. 10. URI: http://hdl.handle.net/2117/385081 DOI: 10.3389/fmars.2023.1129057

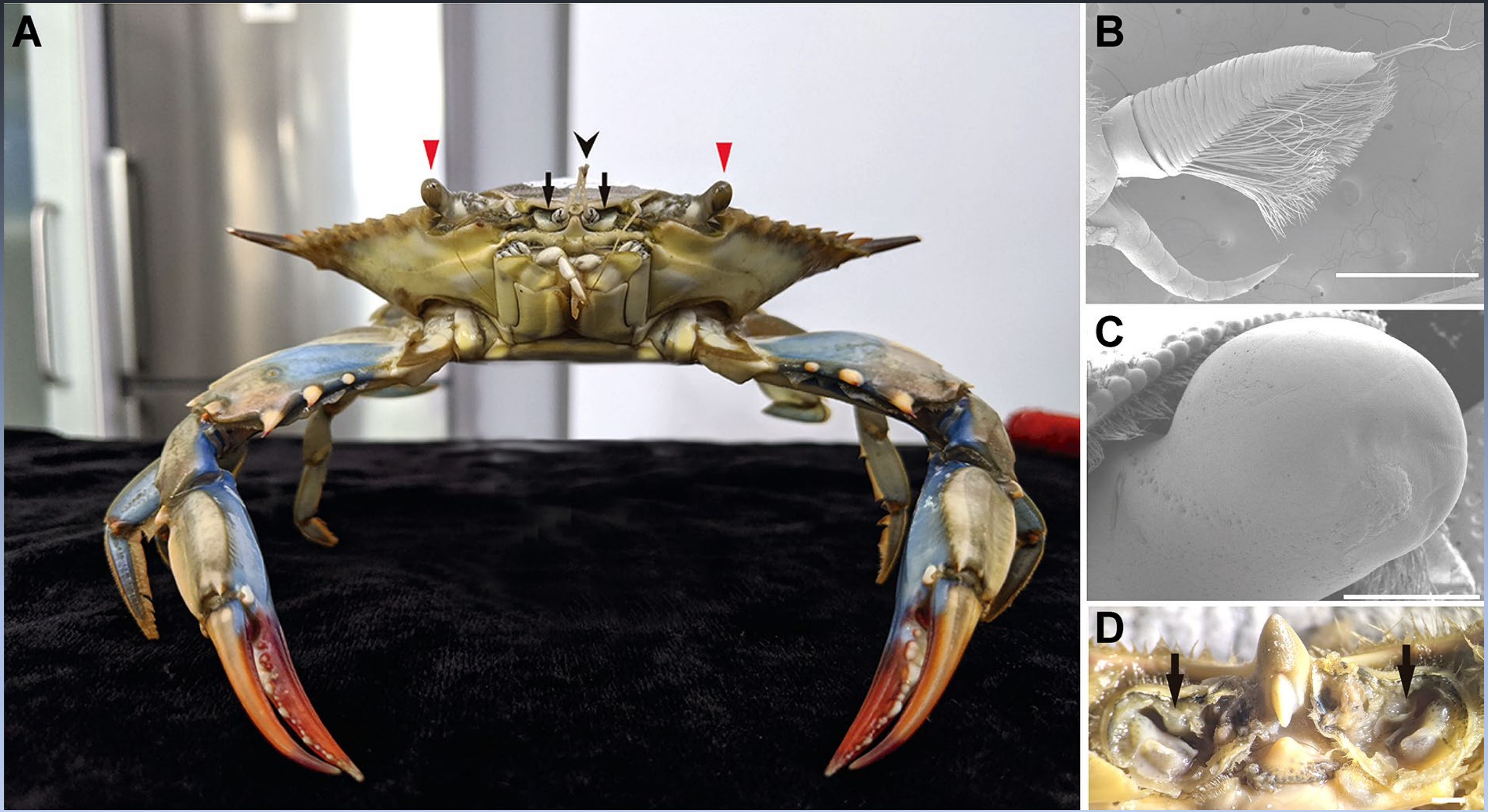
**Bivalves**
- Valve closure
- Alterations in recessing reflex behaviour (establish thresholds of sound detection) (Roberts et al., 2015)
- Flinching behaviour (a rapid retraction of the velum and then returned to position) - commercial scallops (*Pecten fumatus*)- seismic survey. (Day et al., 2016
- Changes in scallop behaviour and reflex responses disruption - 120 days after seismic survey exposure (Day et al., 2017)

**Cephalopods**,
- Startling responses (jetting and inking) - seismic surveys (Fewtrell & McCauley, 2012) and in laboratory conditionss (Samson et al., 2014)
- Habituation (fewer alarm responses with subsequent exposure to noise (Fewtrell & McCauley, 2012), (McCauley et al., 2000; Samson et al., 2014; Mooney et al., 2016).
- Behavioural response to acoustic stimuli in a context of anti-predator defence (Hanlon and Budelmann, 1987; Kaifu et al., 2007)
- Feeding and foraging behaviour altered - different noise stimuli (Jones et al., 2021)

**Crustaceans**
- Alarm behaviour (startle responses) very near from the seismic sound source (Goodall et al., 1990; Christian et al., 2003).
- Suspension of search for food (Wale et al., 2013a)
- Longer time to find refuge (Wale et al., 2013a)
- Increased respiration, decreasing escape responses and reduction on foraging activity in the presence of sound from its predatory species (sensory cue for the presence of fish (Regnault and Lagardere, 1983; Hughes et al., 2014)
- *Nephrops norvegicus* (reduced activity, bury less deeply and flush their burrows less regularly ) (Solan et al., 2016)
- Modify foraging interactions, reducing food aggregation in crabs and release competition for shrimps (Hubert et al., 2018)
- Distance travelled, linear and angular velocity, or alarm responses, intraspecific aggressive encounters and sheltering behaviour (Celi et al., 2013; Filiciotto et al., 2014; De Vincenzi et al., 2015)
- Lobsters and common prawn - modified locomotor activities (distance moved, velocity, proximity with conspecific) (Filiciotto et al., 2014; Filiciotto et al., 2016).
- Modification on antennae movement (Roberts et al., 2016)
- Delaying on Righting reflex (time to right itself) (Day et al., 2016)
- Decreased agonistic behaviour (Celi et al., 2013)
- Behavioural effects on movement (Morris et al., 2020a)
- Habituation to vibrations in crabs - greatest sensitivity to particle motion (Roberts et al., 2016).
- Hermit crabs (*Pagurus bernhardus* - interaction with predator presence reaction, shell size and duration *to* accept the optimal empty shell (Tidau and Briffa, 2019b).
- Adverse effects on the capacity to change the carapace colour to improve camouflage and predator escape responses (Carter et al., 2019).
- Bioturbation may affect intra and inter-specific behaviour on lobster (*Nephrops n*orvegicus) (Solan et al., 2016).

# Marine noise pollution

**Case Studies (BIOACOUSTIC APPLICATIONS to mitigate the effects of aquatic plagues)**



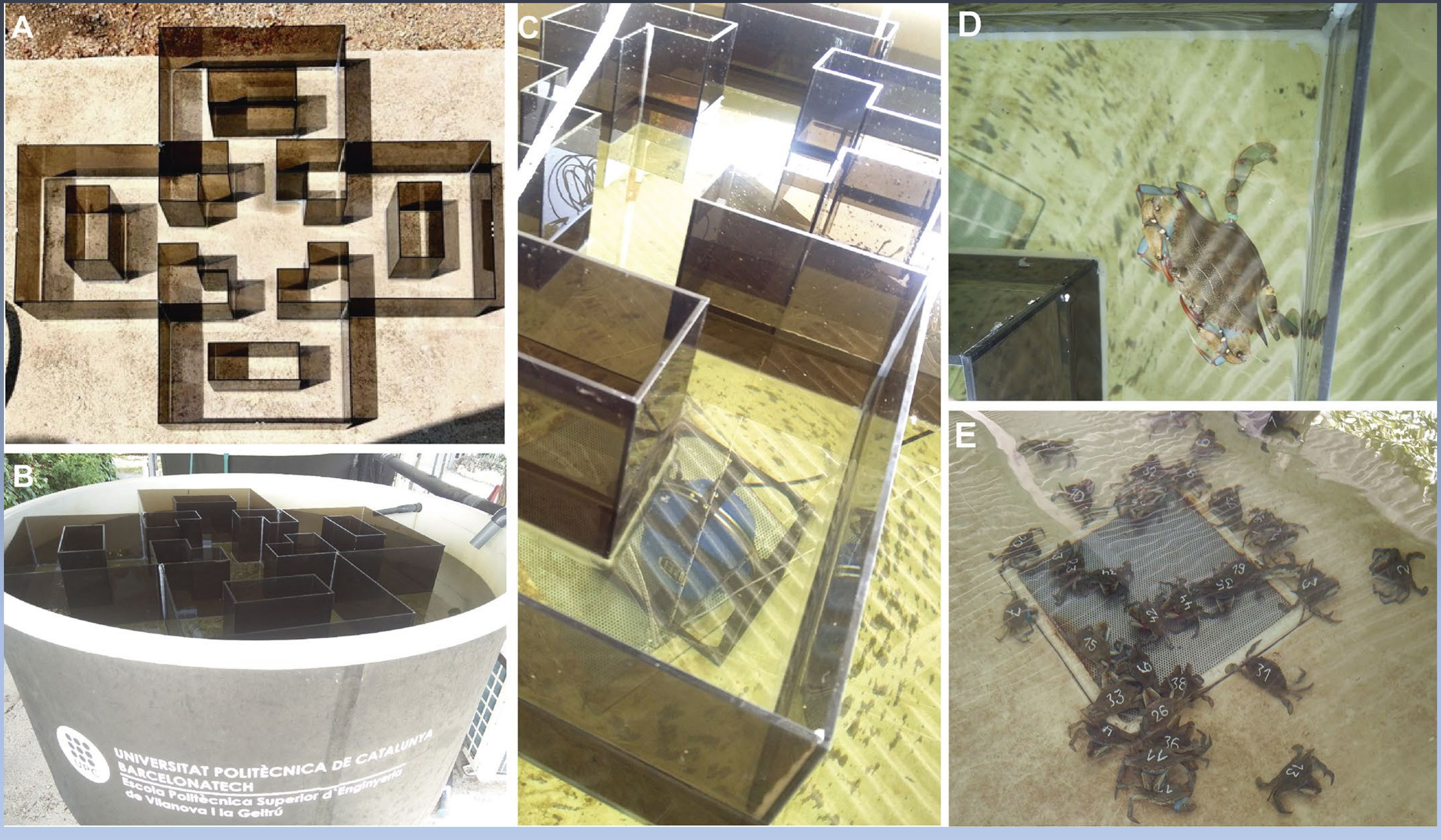

**Blue crab**
**(*Callinectes sapidus*)**

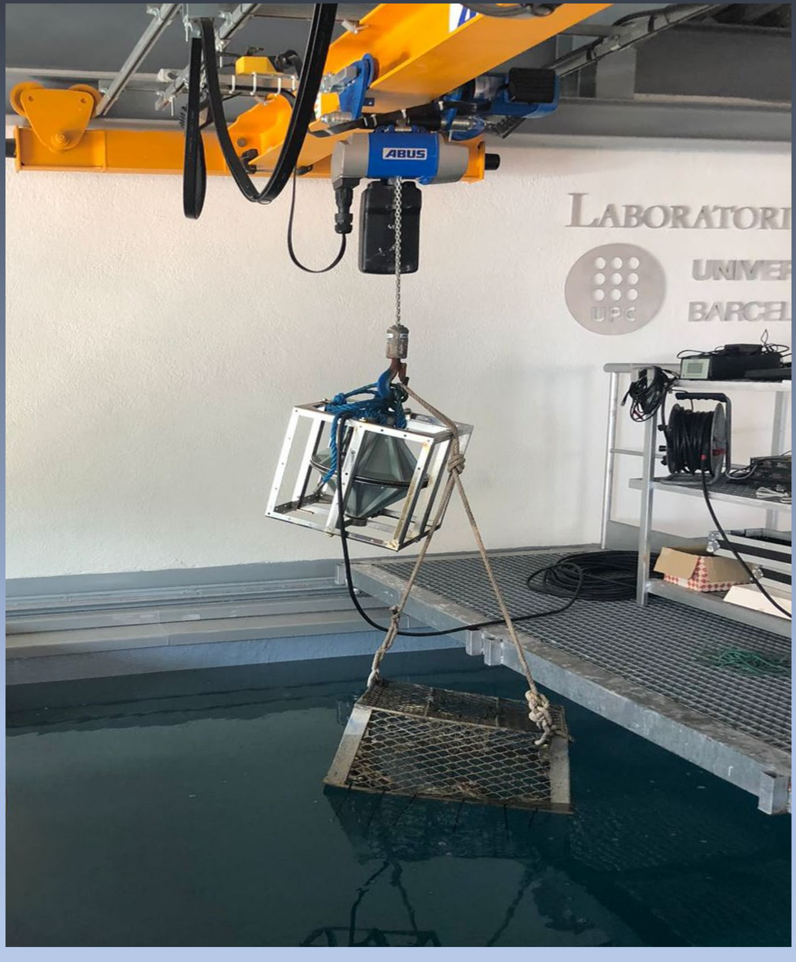
Sole, M. et al. Cross-sensory interference assessment after exposure to noise shows different effects in the blue crab olfactory and sound sensing capabilities. "Science of the total environment", (2023) 873, 162260. DOI10.1016/j.scitotenv.2023.162260

# Marine noise pollution

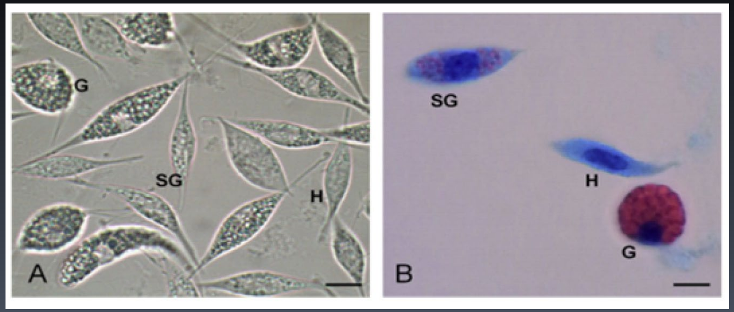
## Case Studies (BIOACOUSTIC APPLICATIONS to mitigate the effects of aquatic plagues)

### Blue crab (*Callinectes sapidus*)



# Marine noise pollution




## Effects of noise on marine invertebrates (Adults) - Physiological effects

**Bivalves**

- Alteration in metabolism related genes (Peng et al., 2016)
- Incresses in levels of biochemical stress parameters measured in their plasma and tissues
- (La Bella et al., 1996; Vazzana et al., 2016; Vazzana et al., 2020a)
- Long-term capability of scallops to maintain homeostasis reduced (Day et al., 2016)
- Decreased respiration (Wale et al., 2019) (Shi et al., 2019),

**Cephalopods**

- Statocyst endolymph changes in the protein content immediately and 24 h after sound exposure (Solé et al., 2019) (proteins related to stress and cytoskeletal structure: Hemocyanin isoforms, tubulin alpha chain and intermediate filament protein down-regulated after exposure)

**Crustaceans**

- Sub-lethal physiological changes (serum biochemistry and hepatopancreatic cells) . American lobsters (*H. americanus*) (Payne et al., 2007)
- Reduction in the rate of growth and reproduction, increase in the level of aggressiveness (cannibalism) and the mortality rate, reduction in feed intake of shrimp *Crangon crangon* (Lagardère, 1982; Regnault and Lagardere, 1983). Reduced growth and reproductive rates are known tertiary effects of stress response (Barton, 2002)
- Alterations on respiration (increase on metabolic rate) Regnault and Lagardere, 1983; Wale et al., 2013b. Wale et al., 2013b),
- Alterations in total protein concentrations in the haemolymph and brain, in DNA integrity, in the expression protein levels of HSP 27 and 70 in brain tissues (Filiciotto et al., 2016)

**Echinoderms**

- Brittle stars (*Amphiura filiformis*) - physiological stress (Solan et al., 2016)
- Sea urchin *Arbacia lixula* significant change in enzyme activity and in gene and protein expression of the HSP70 (Vazzana et al., 2020b).

Sole, M. [et al.]. Marine invertebrates and noise. "Frontiers in marine science", 7 Març 2023, vol. 10. URI: http://hdl.handle.net/2117/385081 DOI: 10.3389/fmars.2023.1129057

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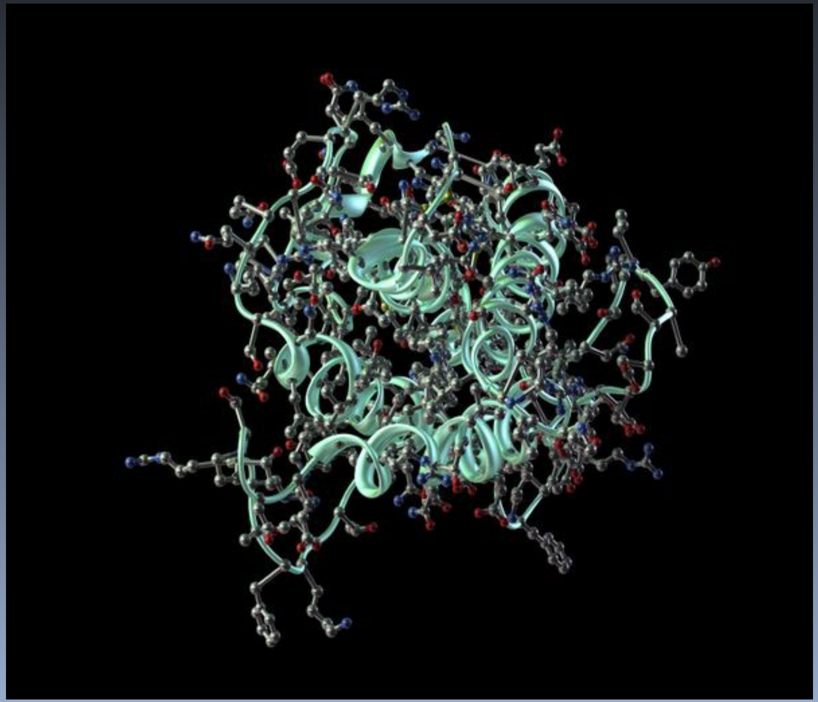
# Marine noise pollution

**Case Studies (Cephalopods)**

**Proteomic techniques**

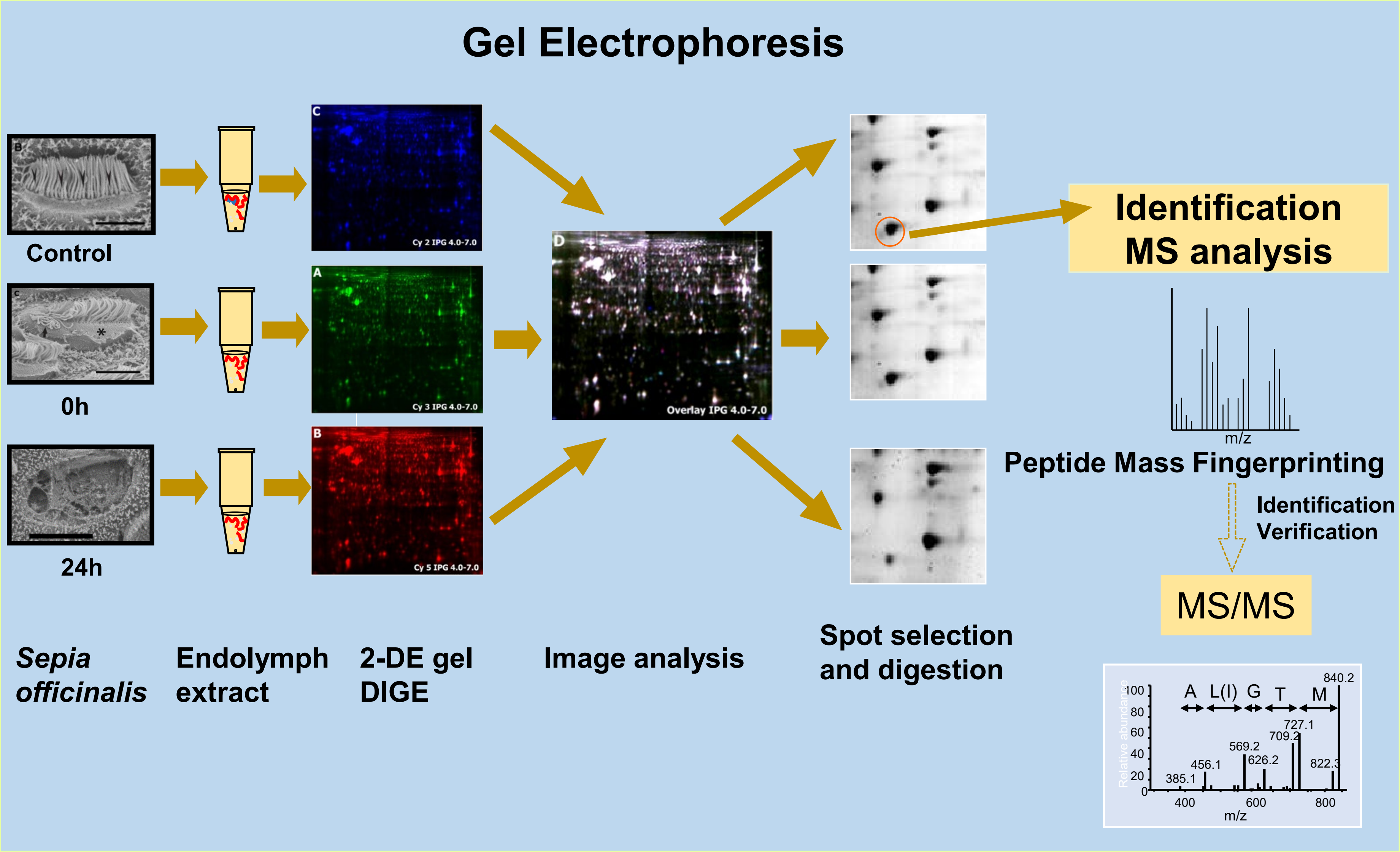


**Research Objective**

To assess the structural effects of low frequency noise exposure on specific statocyst endolymph proteins (biomarkers) of adult individuals of *S. officinalis*, using 2D-PAGE and mass spectrometry techniques.

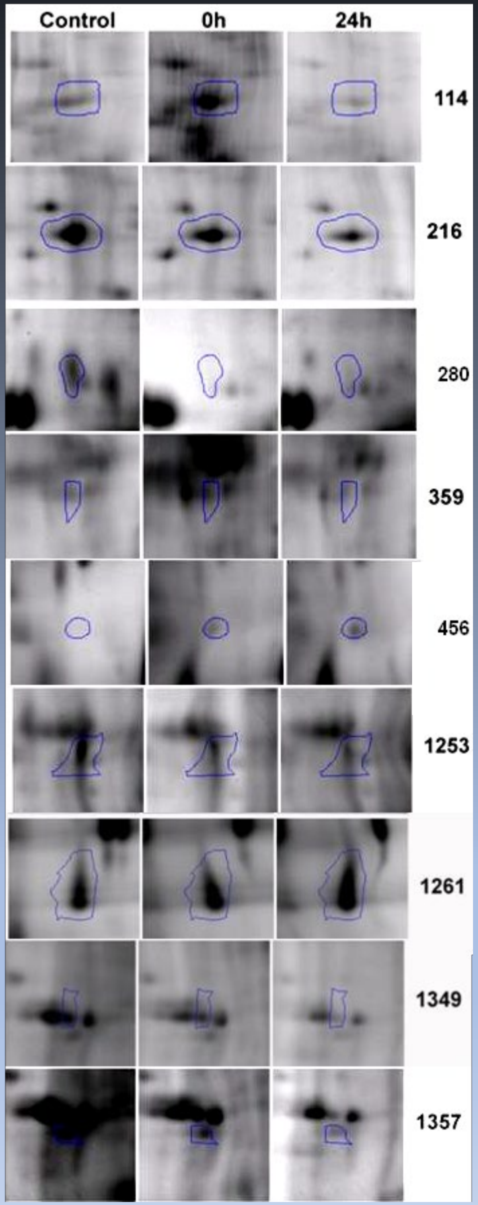
# Marine noise pollution

## Protein identification: Proteomic Techniques



# Marine noise pollution

## Protein identification




| IDENTIFICATION | FUNCTION |
|---|---|
| Hemocyanin, units G and H *Sepia officinalis* (2 spots) | Stress reaction-oxygen transport |
| Elongation factor-1 alpha | Stress reaction - metabolic processes (glucolysis, proteolysis, protein synthesis) |
| Hemocyanin, subunit 2 *Sepia officinalis (7 spots)* | Stress reaction-oxygen transport |
| Thioredoxin peroxidasa | Stress reaction - antioxidant enzime (redox state regulation processs) and cell signaling |
| Tubulin alpha chain | Structural function-cytoskeletal protein |
| Proteasome alpha subunit | Stress reaction- metabolic processes (glucolysis, proteolysis, protein synthesis) |
| 70 KDa neurofilament protein | Structural function - cytoskeletal protein |
| Heat shock protein 90KDa (HSP90) | Stress reaction- folding and unfolding proteins- cytoskeletal proteins interaction |
| Intermediate filament protein | Structural function- cytoskeletal protein |

Solé, M., Monge, M., André, M., and Quero, C. (2019). A proteomic analysis of the statocyst endolymph in common cuttlefish (Sepia officinalis): An assessment of acoustic trauma after exposure to sound. Sci. Rep. 9 (1), 9340. doi: 10.1038/s41598-019-45646-6

# Marine noise pollution

## Effects on populations and ecosystems

- Enormous impact on the **regional population structure** of a species (induced **emigration, unbalanced prey–predator relation, effects on larva development** lead to a **reduced recruitment** (Peng et al., 2015)

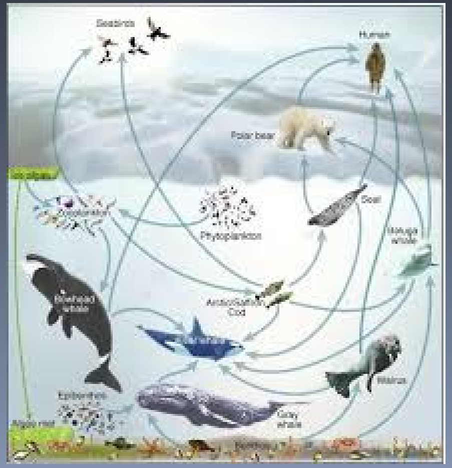
- **Reduction of the population** - decline in the fisheries catch. (Ex: Effects of seismic noise exposure on regional catch rates (snow crabs in Canada (Christian et al., 2004) and rock lobsters and scallops in Australia (Parry and Gason, 2006; Harrington et al., 2010). **No clear**: no negative effects on catch rates of diferent sp. (crabs (Morris et al., 2020b),(cephalopods (La Bella et al., 1996), bivalves (Parry et al., 2002; Harrington et al., 2010), gastropods (La Bella et al., 1996; Christian et al., 2003; Parry and Gason, 2006; Boudreu et al., 2009), and stomatopods (La Bella et al., 1996)

- **Disrupt antagonistic behaviour, the communication, the social grouping and associations** (including their dominance hierarchies and mating systems) and consequently the **capacity to act collectively or mate normally** by **altering the medium** through which signals are transmitted or directly **altering physiology** (Fisher et al., 2021)

- Changes in **mating behaviour and grouping behaviour** in crustaceans (Ruiz-Ruiz et al., 2020; Tidau and Briffa, 2019a): noise-induced **changes in social interaction**

- **Population level compromised** due to changes in predator avoidance behaviours, if sound exposure induces behavioural changes in prey (Walsh et al., 2017) and **predation rates increase** (Chan et al., 2010)

- **Avoidance behaviours**: startling responses on populations that migrate from the areas where seismic surveys are conducted.

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# Marine noise pollution

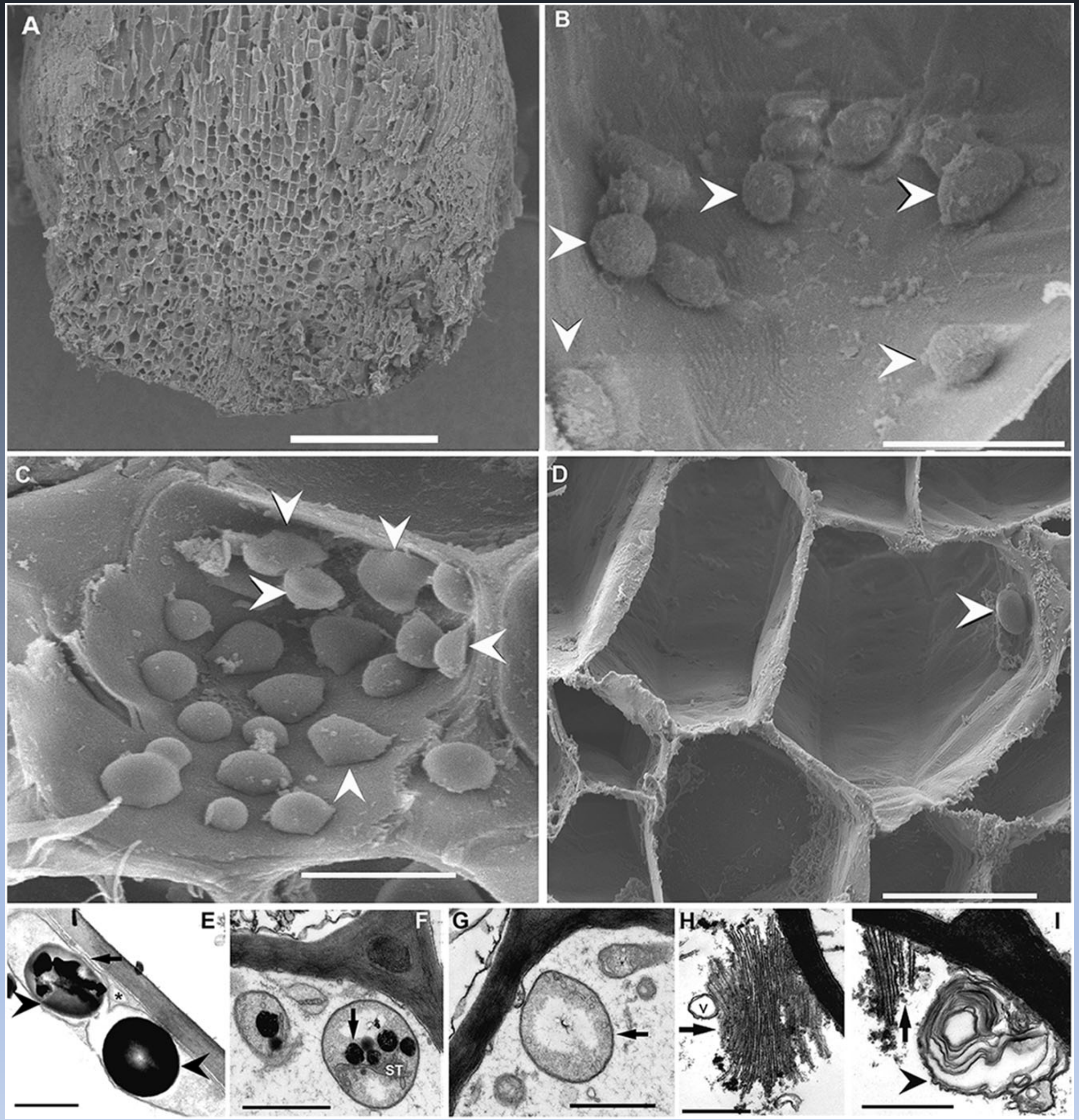
**Effects of noise on marine plants**

***Posidona oceanica* ROOT**

- Number of starch granules progressively decreased after the exposure until their total disappearance

- Control plants showed high number starch-containing amyloplasts - Exposed plants decreasing number of starch grains with time

- TEM presence of plastoglobuli and myelin-like features (massive accumulation of membranes, by vacuolar fragmentation or endoplasmic reticulum disorganization as sound exposure consequence)

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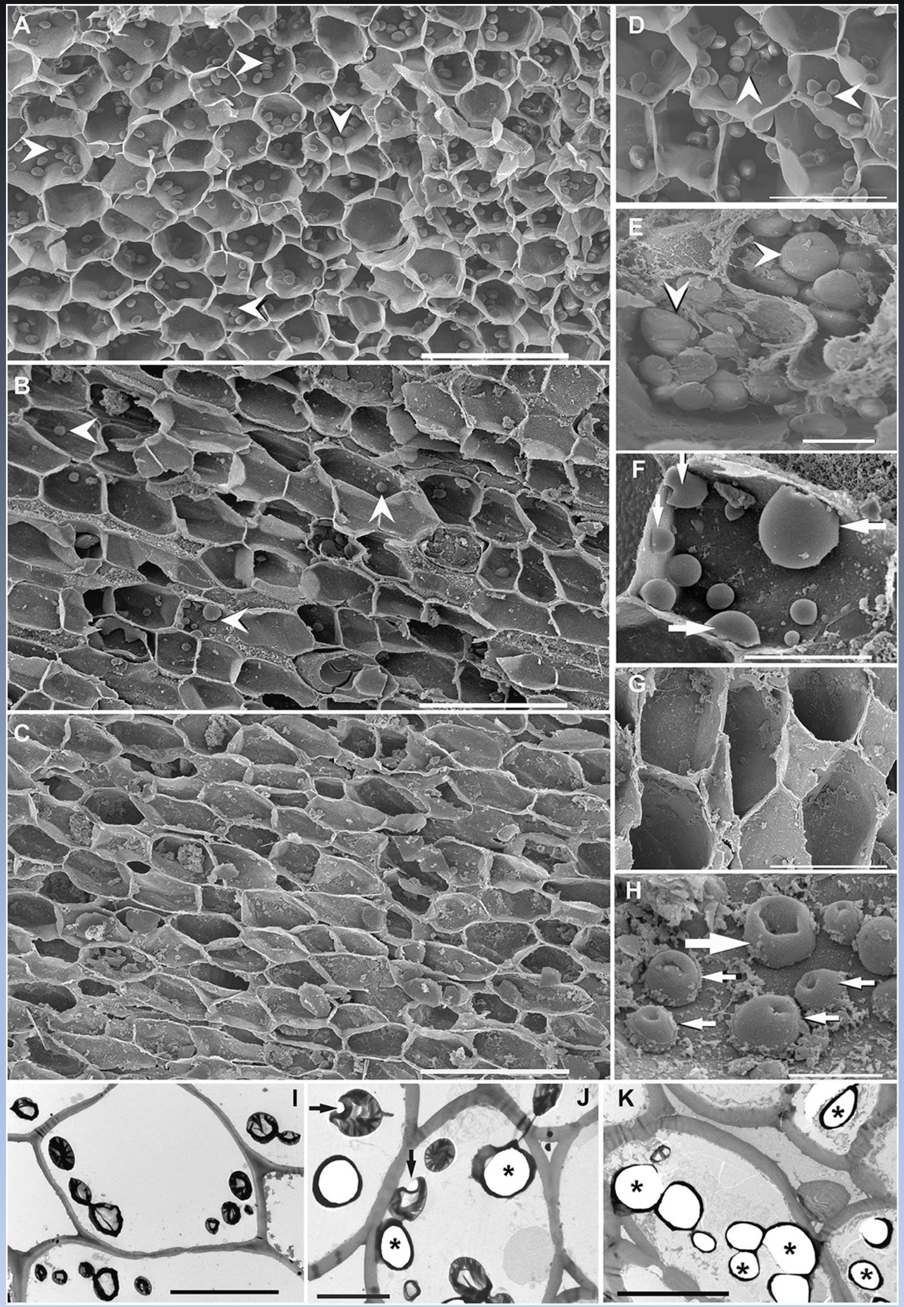
# Marine noise pollution

**Effects of noise on marine plants**

***Posidona oceanica* RIZHOME**

- Number of starch granules progressively decreased after the exposure until their total disappearance
- At 48 h after sound exposure some starch grains
  - deformed structure lacking the typical spherical shape
- In some cases (96 –120 h after exposure), remaining starch grains presented several holes at the surface and a deformed organelle structure, probably because of the expulsion of its inner material visible in TEM

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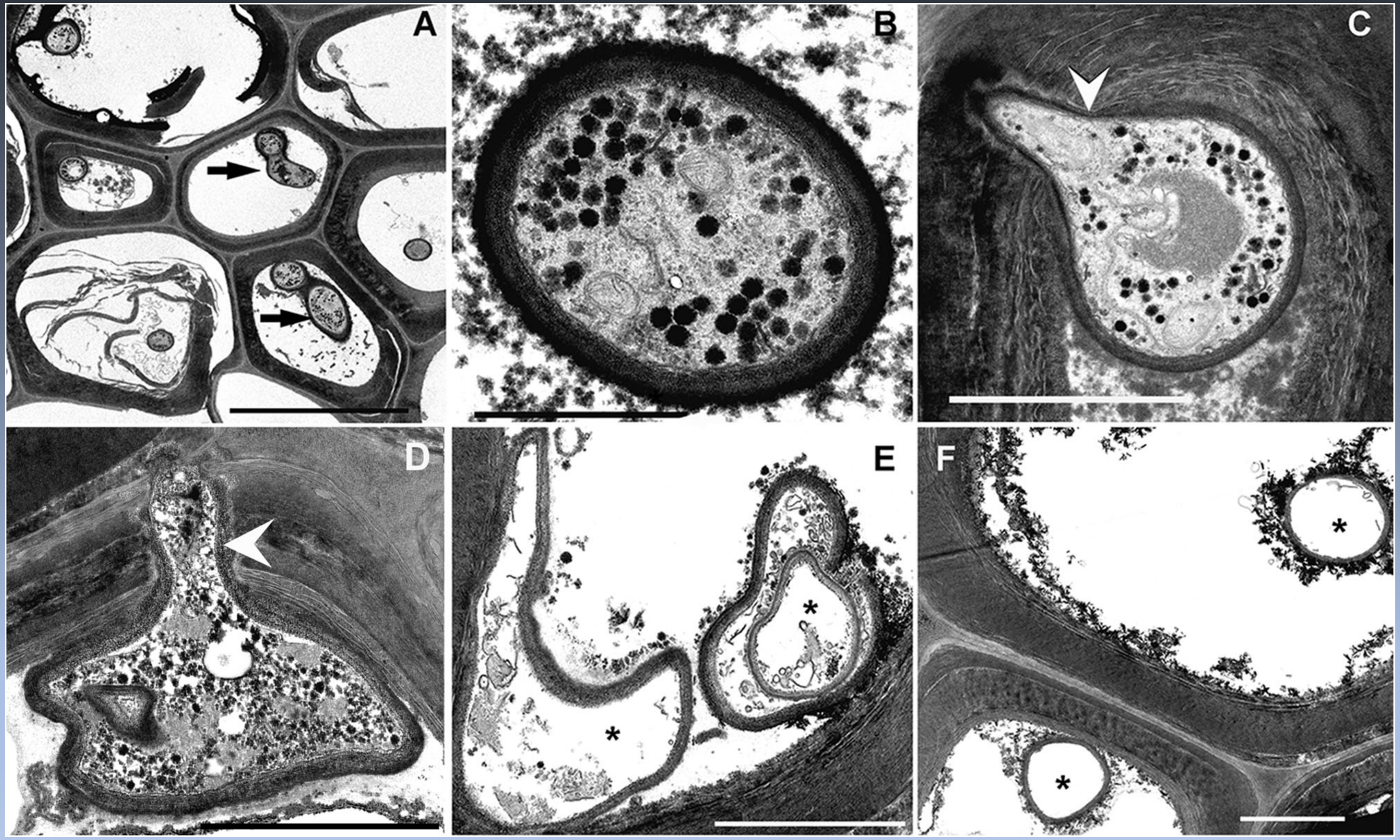
# Marine noise pollution

## Effects of noise on marine plants

### Fungal symbionts of *P. oceanica* roots




- Fungal hyphae colonizing hypodermal cells of exposed *P. oceanica* roots - degraded aspect
- Cytoplasm of the exposed hyphae - progressive alteration of the intracellular organelles with time -totally empty cytoplasm at 120 h after sound exposure

# Gaps and perspectives

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(1) The biological mechanisms of sound detection and production lack of descriptive data for most species.

(2) Some marine invertebrate groups are very poorly investigated – it is needed to provide tools to identify species that are especially vulnerable to noise.

(3) The physical and physiological variables related to stress, energy metabolism and hormones responses need to be improved (including proteomic and metabolomics methods), especially how these changes may influence individual and population health.

(4) More information is needed to predict the noise responses of understudied species or survive in noisy habitats or have a lower auditory sensitivity.

(5) There is a need to undertake and compare large-scale/long term field and laboratory studies.

(6) Adaptation and habituation to long-term noise exposure or a potential recovery from chronic noise exposure has not been investigated.

(7)A standardized protocol in future publications should always include duration, frequency range, weighting filters applied, reference pressure used, source and received levels, distance and duration of recordings, including data on the magnitude and direction of particle motion respect to the source.

(8) When performing field studies a previous characterisation of the local soundscapes should be provided to extract the contribution of noise exposure to potential effects.

(9) The interactions between different stressors (multistressors: in addition to noise introduction, artificial light, habitat fragmentation, global warming, acidification, etc) must be considered when describing noise effects.

(10) Dose-response data is necessary to provide regulators and decision-makers with proper information.