ily cere-
cahier

listening to the tree of life

karen bakker

33

ily cere- cahier 33
a part of:

THE SOUNDS OF LIFE

HOW DIGITAL TECHNOLOGY IS BRINGING US CLOSER TO THE WORLDS OF ANIMALS AND PLANTS

KAREN BAKKER

PRINCETON UNIVERSITY PRESS
PRINCETON AND OXFORD

10

LISTENING TO THE TREE OF LIFE

> Let us bring people back into conversation with all that is green and growing; a universe that never stopped speaking to us, even when we forgot how to listen.
>
> —ROBIN WALL KIMMERER, *BRAIDING SWEETGRASS*

In 2010, fewer than four hundred North Atlantic right whales remained alive off the northeastern coast of the United States. Struggling to recover after the end of industrial whaling, the whales had become one of the most endangered species in the world. That summer, when their traditional territory in the Gulf of Maine was hit by an unprecedented heat wave, their home became the fastest-warming area on the planet.[1] Soon after, the whales disappeared from the gulf. No one knew where they had gone, but scientists suspected they had become climate change refugees, migrating in a desperate hunt for food.[2]

Right whales, one of the largest mammals in the world, nourish themselves primarily on one of the ocean's smallest creatures: copepods. Copepods—zooplankton that form the largest biomass of animals on the planet, the base of many marine food chains—thrive in upwellings of cold, nutrient-rich water. As the heat wave hit the Gulf of Maine, colder waters retreated north and the copepod population declined precipitously.[3] Soon after, the whales also vanished.[4]

A few months later, hundreds of miles to the north, the whales were spotted in the Gulf of St. Lawrence, one of the richest marine zones in the world, where the mighty St. Lawrence River drains the Great Lakes (containing more than a quarter of the Earth's freshwater) into the Atlantic. The whales were not alone in moving north; that year, salmon were seen in Arctic rivers like the Mackenzie, and Atlantic tuna were observed off the coast of Greenland, thousands of miles from their known ranges, hunting for new habitat.[5] The whales had chosen wisely: they had found their way to the Shediac Valley, a biodiversity hotspot, refuge, and nursery for marine life. There, with abundant food, they should have thrived. But the Gulf of St. Lawrence is also one of the busiest shipping zones in the world. The whales had been fortunate to find an abundant buffet, but accessing it required them to navigate the marine equivalent of a twelve-lane highway.

As the whales congregated in the gulf, ships began striking them more frequently. Bloated whale bodies washed up on shore, their skin gouged by propeller cuts and distorted by blunt-force trauma.[6] A record number of whales became entangled in fishing gear, which often proved fatal. In 2017, more than a dozen whale deaths on the Canadian side of the border were attributed to fishing gear entanglement and ship strikes; an additional eight whales died over the following two years.[7] Many more bodies likely sank to the ocean floor before being spotted, a potential death knell for a species with so few remaining individuals.[8]

Government officials weren't sure what to do. It was hard to pinpoint the whales' location, and data from aerial surveys were often outdated, sometimes up to a year old.[9] Conventional whale protection strategies—such as fisheries closures, designation of critical habitat areas, and modifications to shipping routes—are based on the assumption that whales visit the same foraging grounds at the same time each year. But with rapidly shifting ocean conditions, no one knew where the whales would appear next. Scientists asked for blanket restrictions on shipping: speed limits and fisheries closures that would last until the whales' new migration patterns could be established. But fishers and shipping companies protested. The politicians sided with industry; in the face of uncertain science with insufficient data, fisheries and shipping companies carried on with business as usual.[10] One year passed, then two; the whales kept dying. By 2019, one in ten whales had died from ship strikes or fishing line entanglement, over fifty in all; time was running out to save them.[11]

Two challenges stood in the way of preventing more whale deaths: figuring out where the whales actually were, and alerting ships quickly enough so that they could avoid striking the whales. Bioacoustics emerged as a novel solution to both challenges. Fisheries officials had been relying on aerial surveys to monitor the whales, but this method was expensive, inefficient, and often hampered by bad weather conditions. Locally based biologists like Kimberley Davies, a professor at the University of New Brunswick, knew that passive bioacoustic monitoring could provide continuous surveys of whale locations with greater accuracy and lower cost.[12] Over the previous decade, marine biologists like Davies had been developing and refining passive acoustic monitoring systems as a means of tracking whale movements; their data confirmed that many whales were spending more time in northern latitudes, and pinpointed whale location with high accuracy.[13]

The key to Davies's approach was an innovative bioacoustics device: an underwater, autonomous acoustic glider equipped with hydrophones—somewhat like a marine version of an aerial drone. These gliders, Davies explains, "can stay out in all kinds of weather, persistently monitoring twenty-four hours a day, seven days a week."[14] When Davies started reporting the whale location data in 2019, she sounded the alarm. As her gliders moved back and forth across the water, the data showed that whales were using a much larger area than previously understood. Davies warned officials: unless more extensive shipping and fishing restrictions were implemented immediately, over a large expanse of ocean, more whales would die. In the face of their objections, she presented her bioacoustics-based solution. If a right whale is detected by a glider, the location is transmitted to government officials, fishers, and ships' captains, and a large area around the position of the detection (approximately 1,000 square miles) is closed to specific types of fisheries, including lobster and crab, for fifteen days.[15] In some areas, if a whale is detected a second time, the area will be closed for the entire fishing season. Moreover, within designated slowdown zones, all ships are required to abide by mandatory speed limits (10 knots over the ground).[16] The slower a ship travels, the less likely a strike is to be fatal. The boundaries of these zones are dynamic and depend on whale sightings and ocean conditions, such as water temperature, which influences where whales gather. In zones where whales are at higher risk, ships that exceed the speed limit are subjected to fines up to $250,000.[17] The data on whale locations and speed restrictions is placed on open-source maps, which are broadcast to all ships in the area, so pleading ignorance is not an option.

After extended negotiations, Canadian government officials adopted the bioacoustics-based system as part of their governance framework for the Gulf of St. Lawrence.[18] Davies's gliders were repurposed for use in the new mobile marine protected area. The program was an immediate success: within hours of their first launch, the gliders detected whales, signaling ships to slow down. In 2020 and 2021, there were no recorded right whale deaths in the Gulf of St. Lawrence due to ship strikes.[19]

The tale of the North Atlantic right whales is a parable about a digital future in which bioacoustics could be mobilized to protect endangered species worldwide. Enabled by a handful of aquatic drones and an artificial intelligence algorithm in a small university lab, a population of four hundred whales now controls the movements of tens of thousands of ships, in a watershed that is home to forty-five million people. Digital bioacoustics, in other words, enables us not only to eavesdrop on whales but also to protect them—simply by staying out of their way.

Similar systems are now being built around the world, in both terrestrial and aquatic environments. The next step, once machine learning algorithms are sufficiently reliable, is to move these algorithms directly onto the sensors in the field. If algorithms within each sensor can analyze the data in real time, this opens up new possibilities for conservation. For example, in a national park, real-time detection of gunshots by an AI-enabled acoustic sensor could trigger an immediate warning to an antipoaching patrol. Mobile protected areas—supported by real-time bioacoustics data—could play an important role in the future of environmental conservation.

To achieve this goal of bringing computation and data storage onto sensors in the field (which researchers sometimes refer to as "edge computing"), two major challenges need to be addressed: a reliable supply of power for sensors and reliable communication networks, even in remote areas without cell phone coverage. Experts feel that these challenges are likely to be resolved in the next ten years; for example, power issues may be resolved by new sensor designs that do not require as much power or use batteries, and new satellite-based global internet systems may resolve the communications challenge. Some researchers predict that this "batteryless internet of sounds" will be operational in less than a decade.[20] If this prediction comes true, it would enable real-time acoustics-based environmental conservation to protect endangered species, from the busiest to the most remote areas of our planet.

The Whale That Steered the Ship

To be successful, bioacoustics-based conservation systems require humans to accept something very novel: changing their behavior in response to something we can't see or hear. It's one thing to slow down if you see a moose crossing the road; it's another matter to divert a cargo ship from its course because your computer tells you it detected a whale nearby. Operationalizing bioacoustics-based conservation schemes depends on fostering trust in these novel technologies, and belief that the outcomes—saving endangered species—outweigh the costs.

One of the most ambitious bioacoustics schemes in the world, launched off the California coast, is attempting to change the mindset of the global shipping industry. Observers are watching closely; if the just-in-time shipping industry consents to bioacoustics-based conservation, this will set an important global precedent. The California case is emblematic of the whale conservation challenge globally: as shipping has grown exponentially with globalized trade and large ships have increased their average speeds, rates of whale strikes have increased in many high-traffic areas.[21] The Santa Barbara Channel, just north of Los

Angeles, is one of the busiest shipping routes in the world, where it is not uncommon to see tankers the length of skyscrapers. It is also the traditional migration route and feeding ground of endangered fin, humpback, and blue whales, which, as the largest animals on Earth, are particularly vulnerable to ship strikes. In the channel, ships tower so high above the ocean's surface that whales are difficult to see, let alone avoid. A decade ago, the federal government created voluntary slow speed zones—which have been shown to dramatically reduce whale deaths from ship strikes[22]—but less than half the ships follow the voluntary speed limit.[23] In Southern California, 2018 and 2019 were the worst years on record for fatal whale strikes by ships. Even these dire statistics likely underestimate the true toll, as most corpses sink before they wash ashore.[24]

In response, a team led by marine scientist Morgan Visalli at the University of California, Santa Cruz, created a novel bioacoustics whale protection system. Christened Whale Safe, it combines bioacoustics with three other digital technologies.[25] First, an underwater monitoring system uses bioacoustics to automatically detect whale calls;[26] an array of underwater microphones (hydrophones) detects and processes sounds using artificial intelligence algorithms that are able to not only identify whales but also specify whether they are blue, humpback, or fin whales. This data is then sent via satellite to whale scientists for review and confirmation. Second, marine scientists in Santa Barbara run models that forecast probable whale location, combining oceanographic data (ocean temperatures, seafloor topography, and currents) with past studies of whale location using satellite tags.[27] As ocean temperatures and conditions shift daily, so do whales' movements; the models give near-real-time, highly accurate predictions. Third, the forecasts are complemented by actual whale sightings, which citizen scientists, mariners, and whale-watching boats record through mobile apps.[28] Fourth, Whale Safe tracks ships' locations,[29] and the data is layered together to create a whale presence rating, similar to a school zone notice (green = no whales; yellow = proceed with caution; red = whales present, go slow). The rating is then communicated to ship captains in real time via their smartphones or tablets.[30] Captains are encouraged to slow down and post more lookouts; the ships are then tracked to see whether they comply with voluntary slow-speed zones. Whale Safe also helps regulators decide whether and how to extend slow-speed zones by letting them know if whales are spending more time in an area than expected. The Whale Safe team then monitors ships and publishes public report cards that show how well ships are complying with speed restrictions. Ships that don't comply receive a "failure" rating. To further enhance compliance, scientists are developing infrared thermal imaging cameras to mount on the bows of ships—the equivalent of a dashcam—that will detect whales in real time, as well as whale strikes. In the future, if ships don't comply with the whale-designated avoidance zones, they'll be caught red-handed.[31]

Whale Safe is an exponential improvement over previous methods, which were imprecise and reliant on patchy data, and which required scientists to retrieve recording instruments from the ocean before analyzing the data, resulting in time lags ranging from weeks to months. Now, scientists can generate near-real-time whale presence forecasts, much like weather forecasts, that provide estimates of the probability of whales appearing in different places.[32] After a successful launch in mid-2020, the team is now planning to expand to San Francisco Bay.

Similar schemes have sprung up in other parts of the world. In the South Taranaki Bight (which lies between New Zealand's North and South Islands), for example, researchers have recently used bioacoustics to identify a unique resident population of blue whales. The lead researcher, Leigh Torres, was sharply criticized for advancing a resident whale hypothesis; shipping and mining industry advocates argued that the whales were part of a migratory population (as most whales are indeed transient). But Torres's meticulous bioacoustics research, combined with genetic testing, proved that the blue whale population was genetically distinct, and resident year-round.[33] When applications for seabed mining in the area were put forward, the newfound knowledge of this unusual population spurred a national movement to save the New Zealand blue whale, culminating in a Supreme Court ruling to revoke the seabed mining permits and pressure the government to ban seabed mining altogether.[34] In the meantime, researchers have developed a predictive model for blue whale locations that will enable dynamic, mobile protected areas to be created in the South Taranaki Bight.[35]

Visalli points out that when ships slow down, the wider community benefits; slower ships not only hit fewer whales but also create less noise pollution, release fewer environmental pollutants, and emit less carbon dioxide. Saving whales from ship strikes also benefits the global environment by helping mitigate climate change. Whales are highly efficient at carbon storage. When they die, each whale sequesters an average of 30 tons of carbon dioxide, taking that carbon out of the atmosphere for centuries. For comparison, the average tree absorbs only 48 pounds of CO_2 a year.[36] From a climate perspective, each whale is the marine equivalent of thousands of trees. Whales also help sequester carbon by fertilizing the ocean as they excrete nutrient-rich waste, in turn increasing phytoplankton populations, which also sequester carbon—leading some scientists to call them the "engineers of marine ecosystems." In 2019, economists from the International Monetary Fund (IMF) estimated the value of the ecosystem services provided by each whale at over $2 million USD. They called for a new global program of economic incentives to return whale populations to preindustrial whaling levels as one example of a "nature-based solution" to climate change.[37]

Calls are now being made for a global whale restoration program, to support both marine biodiversity and climate change mitigation. Researchers are currently developing the governance architecture that would extend bioacoustics monitoring, and protected areas, across the entirety of the world's oceans. Today, bioacoustics whale protection systems exist in isolated areas. But in the future, a network of bioacoustics listening stations could create flexible "whale lanes" across the world's oceans, controlled by the whales themselves.

Mobile Protected Areas

The most recent report on the state of the oceans from the Intergovernmental Panel on Climate Change (IPCC) predicts that marine heat waves, rising seas, dying corals, and vanishing sea ice will devastate current levels of biodiversity.[38] With rising global sea surface temperatures and changing ocean currents, as well as increasingly common extreme weather events, massive migrations of marine populations are already underway.[39] As the world's ocean creatures move in unpredictable ways, mobile protected area schemes in the world's oceans might become a necessary, widespread conservation measure. Listening for their presence using digital bioacoustics will become even more urgent; a "new normal" in marine governance.

Some of the underlying architecture for mobile marine protected areas already exists in the form of acoustic telemetry networks, such as the Integrated Marine Observing System (IMOS) in Australia, the NOAA Ocean Noise Reference Station Network in the United States, and the Acoustic Tracking Array Platform in South Africa.[40] These listening networks can help determine the presence of endangered species and estimate how marine organisms are moving, in order to enable marine protected areas to respond to changing environmental conditions.[41] As new areas of the melting Arctic open up to shipping, for example, new means of preventing ships from striking whales will be needed in zones like the Bering Strait—a bottleneck for both ships and migrating whales.[42]

These mobile marine protected areas are a hopeful example of novel strategies that are emerging as scientists and conservationists apply digital tools to pressing environmental challenges. While humans have tracked the movements of animals for millennia—for survival, as well as for managing and protecting wildlife populations—the degree of surveillance afforded by digital tools is unprecedented. In the past decade, the miniaturization and proliferation of new, inexpensive, internet-enabled tracking technologies has led to a new golden age of biologging, which enables accurate and precise monitoring even of small species, such as insects, as well as long-distance migratory species, such as salmon and turtles.[43] Some of this tracking is visual, but much of it is acoustic.[44]

Why is this important? As biodiversity loss accelerates, the planet's sixth mass extinction is under way. Many animals are responding by changing their habits—for instance, becoming nocturnal—or by moving to new habitats. As humans continue to modify terrestrial and marine habitats, as well as the global climate, this creates a new problem for conservation: habitats of endangered species are disappearing, or shifting geographical location, due to climate change. The designated zones created to protect them no longer contain the food or appropriate habitat they need to survive. For an increasing range of species, these areas need to be geographically mobile.

As we add an estimated two billion people to the planet over the next few decades, bioacoustics is one of our best options for balancing human activities with other species. Digital acoustic monitoring, combined with advanced forms of artificial intelligence, like machine learning, enables scientists to model animal biodiversity in real time; this can be used to track vocally active species, as well as nonsoniferous species that depend on or closely interact with sound-producing species.[45] In turn, this could help reorient or constrain the movements of humans in the most sensitive places, at the most sensitive times. Rather than a small number of parks, large numbers of evolving “safe zones” could be created that follow animals as they move throughout the world’s rapidly changing habitats. Of course, bioacoustics-enabled conservation schemes won’t address all threats to biodiversity, such as chemical pollution. But bioacoustics-powered conservation still offers one of the best means available to protect biodiversity.

Bioacoustics technologies could also be deployed to prevent conservation crimes. For example, bioacoustics is now being used to monitor the spatial distribution and hotspots for blast fishing (also known as dynamite fishing). The practice, in which fishers use illegally sourced or homemade explosives made from kerosene and fertilizer, has been described as the marine equivalent of elephant poaching; the fishers target coral reefs with high fish densities, using explosives to kill and stun fish so they may be more easily harvested. Deep ocean fish (like tuna) are also increasingly targeted with explosive blasts and then collected by scuba divers. Survivors are likely to be maimed and have permanent hearing loss, affecting future survival rates. Blast fishing, widespread in the Coral Triangle in Southeast Asia, as well as in Tanzania, is difficult to monitor and enforce; typically, small-scale fishers find it easy to evade infrequent patrols.[46] Passive acoustic monitoring, combined with automated algorithms for detecting explosive blasts, can easily pinpoint illegal fishing at distances up to 30 or 40 miles away, helping law enforcement quickly identify perpetrators.[47]

In addition to helping humans locate or avoid endangered marine life, acoustic technologies can also help marine life avoid humans. As global concern has grown about massive rates of fisheries bycatch (particularly turtles and dolphins, but also whales), acoustic alarms have been developed to warn marine mammals and fish. Today, hundreds of thousands of digital acoustic deterrent devices attached to boats, nets, docks, and pens are used to alert marine life; deterrents can even be calibrated to specific species.[48] Some worry, however, that alarms may cause more harm than they prevent. For example, acoustic deterrents that work for some species can negatively affect others; much like installing a bright light to deter burglars might create light pollution that irritates the neighbors.[49] Moreover, cumulative noise from acoustic deterrents may also result in acoustic masking—a sort of fuzziness in the acoustic space—even at relatively low noise levels; this chronic background hum might not kill marine animals immediately, but it may reduce the quality and range of their communication space; animals might go quiet or be able to listen only over shorter distances. For a fish or a dolphin, this would be like going slowly deaf and blind.[50] In response, some in the marine bioacoustics research community have begun calling for quieting technologies and alternatives to acoustic deterrents.[51] Yet even if we decide to abandon acoustic deterrents, this alone will not address the more general and much larger threat faced by marine life: an exponentially increasing onslaught of environmental noise.

Silencing a Noisy Ocean

On the morning of September 11, 2001, biologist Rosalind Rolland was getting ready to launch her boat in the Bay of Fundy, into the placid waters on a brilliant, sunny fall day. When the news of the attacks came across the radio, it felt surreal. After a while, the crew decided to head out onto the ocean, in defiance of the fear they felt, because the bay was "calming for the soul," as Rolland put it.[52] At sea, her team busied themselves with the task at hand: collecting whale fecal samples as part of a study on the health and reproduction of right whales. Back in the lab, they would analyze their samples for hormone levels linked to whale stress and health.

Oceanographer Susan Parks was also out in her boat, collecting data for a study on the social behavior of right whale mothers and calves. Although most ships docked for the week following the attacks, Parks continued her recordings in the bay. Two of the only whale researchers to continue working out on the bay during this exceptionally quiet period, Parks and Rolland realized only months later that their data could be combined to answer a groundbreaking question: Could lower noise levels in the ocean be correlated with lower stress levels in the whales?

This question is an urgent one, given that marine noise has doubled every decade since the 1950s in many ocean regions.[53] This is largely the result of the increasing industrialization of the ocean.[54] The growth and globalization of trade has led to a tenfold increase in the tonnage of commercial ships. In recent years, the race to colonize deep-sea oil and gas resources has led to a surge in seismic exploration; this, combined with increased boat traffic, sonar, construction, and acoustic deterrent devices, has exponentially increased the industrial clamor in the oceans.[55]

Parks and Rolland's experiment thus captured the effects of decades of stress on whale populations. The results of their combined analysis made headlines: in the temporary hush that followed 9/11, the whales' stress levels were markedly lower.[56] As marine noise dropped to one-quarter of previous levels, a similar decrease was observed in stress-related hormone metabolites in the whales. As ship traffic and noise rose again, so too did the whale's stress hormone levels. Similar effects have been observed in humans; noise exposure is associated with higher blood pressure, higher levels of stress hormones, cardiovascular effects, and coronary heart disease in humans.[57] But no one had previously demonstrated the effects of noise pollution on whales.[58]

Curious researchers began running experiments with other marine animals, finding similar results for a broad range of species—even in invertebrates like squid.[59] Twenty years later, the evidence is conclusive: marine noise pollution not only increases stress levels in marine animals but also has many detrimental health effects. Even low-intensity sounds, such as those from distant cargo ships—or even distant cars and airplanes—can cause octopuses to hold their breath and oysters to shut their shells.[60] The range of negative effects caused by cumulative marine noise is staggering: it can delay development, hamper reproduction, stunt growth, disturb sleep, and even kill creatures outright.[61] Underwater seismic exploration is one particularly destructive source of noise pollution: a single shot from a seismic survey air gun can deafen fish and kill zooplankton—the basis of the marine food chain—up to a mile away from the detonation site, as well as cause hearing loss in larger marine mammals, like seals and whales.[62] And because sound travels so well underwater, the effects are felt not only by individuals but also across entire marine ecosystems.[63]

Similar negative health effects attributed to noise have been documented in terrestrial species.[64] Anthropogenic noise disrupts reproduction, foraging and hunting, migration, and activity patterns; it also interferes with animals' neuroendocrine systems (raising cortisol levels), physiology (raising respiration rates), and ability to communicate—making it harder for them to gather, mate, hunt, and socialize.[65] When human-generated noise increases, animals raise their voices, just like humans raise their voices to be heard against a background of loud noise; this may deplete animals' reserves, leaving less energy available for other vital activities.[66]

If animals try to flee loud noises, other ecological processes—like seed dispersal and pollination—are affected.[67] In one innovative "phantom road" experiment, researchers placed fifteen bullhorn speakers along a roadless section of forest in Idaho's Lucky Peak State Park. The speakers played recordings from a highway and measured birds' responses. One-third of birds avoided the phantom road altogether; young (particularly year-old) birds were the most likely to vanish. The birds that remained showed declines in body condition and struggled to put on weight—a troubling result, given that stopovers to refuel are necessary for the survival of many migratory species. By 2050, the researchers note, enough new roads will be built to circle the Earth more than six hundred times; whether mitigation measures can lessen the impact of the resulting anthropogenic noise is doubtful.[68] Even in parks and protected areas, animals are already contending with a growing deluge of human noise.[69]

Perhaps most worrisome, it appears that noise pollution disrupts embryonic development across a wide range of species. Prenatal sounds shape animals' chances for survival, as embryonic acoustic developmental programming affects animals' physiology and cognition through changes in brain connectivity, endocrinology, and gene expression. In healthy ecosystems, this helps animals adapt to their environments; the young of many species recognize their parents' calls when they hatch. Some species, like zebra finches, even modify their size in response to the types of calls their parents make before they are born. Disrupting soundscapes may be profoundly damaging to organisms in ways we have yet to fully understand.[70] What we do know is that animals are extremely sensitive to even small changes in noise; in one study, the impact of motorboats on fish embryos was found to depend on engine type—while any boat motor raised embryo heart rates, two-stroke outboard-powered boats had more than twice the effect of quieter four-stroke-powered boats.[71] An article in *Science* grimly summed up the results: human noise is scrambling the eggs of baby fish.[72]

Songs of Seagrass

The devastation of noise pollution, particularly in the marine world, is underscored by a recent study of one of the most ancient plants on Earth: seagrass meadows, the Great Plains of the sea. With the exception of Antarctica, our planet's marine coastal zones were once abundant with seagrass. Rivaling coral reefs in their extent and importance, seagrass meadows provide food and shelter for the young of many sea creatures, protect coasts against erosion, enable nutrient cycling, stabilize the seafloor, and improve water quality. And just like terrestrial forests, seagrass also plays a major role as a carbon sink, helping stabilize our global climate.[73] In the past several decades, catastrophic seagrass loss has occurred in many of the world's coastal zones; seagrass meadows the size of the Amazon have vanished.[74] Scientists blamed the devastation on a range of threats—climate change, chemical pollutants, boat anchors and dredging, and hypersaline water from desalinization plants. But Marta Solé, a senior researcher in environmental engineering at the Universitat Politècnica de Catalunya, BarcelonaTech (UPC), wondered if noise pollution might also be to blame.

Solé, working with her PhD supervisor, Michel André, had already earned a reputation for unconventional research, studying the effect of human-made noise on marine creatures without ears: cephalopods (like octopuses), cnidarians (corals and jellyfish), crustaceans (like shrimp), and sea lice.[75] Still, her proposed study of the noise sensitivity of marine plants was uncharted territory. Solé decided to focus on the oldest seagrass in the world: *Posidonia*. Named after the Greek god of the sea, the *Posidonia* fossil record dates back to the Cretaceous period. One particular species, *P. oceanica*, is a slow-growing, clonal seagrass endemic to the Mediterranean, which develops networks of roots and rhizomes that can stretch several meters deep. At one time, *P. oceanica* covered the entire coastline; its free-floating fruit was known as the "olive of the sea."[76] The seagrass meadows are ancient: one colony discovered off the south coast of Ibiza is over a hundred thousand years old, quite possibly closer to two hundred thousand—which would make it the oldest living plant in the world.[77]

Solé's earlier research had shown that cephalopods hear sound through small sensory organs called statocysts.[78] When exposed to noise frequencies similar to marine seismic testing and boat noise, damage to statocysts is stark: they swell, explode, and die—much like a human eardrum might be damaged by loud noise.[79] Embryos were equally harmed, with extensive epidermal lesions and damaged cilia.[80]

Could marine plants be similarly affected by marine noise pollution, wondered Solé?[81] Seagrass, like other marine plants, has an analogue to statocysts: organelles called amyloplasts that help the plant orient to gravity, direct its roots, and also detect sound through particle motion in water.[82] The researchers knew that amyloplasts were found in high concentrations in certain cells in the root caps and rhizomes of *P. oceanica*. Would loud sounds harm seagrass the way they harmed the octopuses?

Just as she had done with marine animals, Solé assembled a sample of seagrass plants in tanks in the lab.[83] The control group was left untouched, but the test group was blasted with loud, low-frequency noise similar to the sounds generated by industrial activity, such as shipping and underwater seismic testing. She then examined cells in the roots and rhizomes, as well as the fungal symbionts attached to the roots. In the control group, the amyloplasts were undamaged. But in the group of plants subjected to loud noise, the amyloplasts were severely deformed, and their numbers decreased dramatically. Under the scanning electron microscope, the researchers observed eerie similarities with the octopus statocysts: lesions and blasted-open cells leaking their contents through gaping holes. Just like the octopuses, the seagrass had severe, permanent damage to their sensory organs. This damage, the researchers surmised, could affect the ability of the plants to sense gravity and store energy—two functions basic to their survival. Even more worrisome: the symbiotic fungi attached to the roots were also damaged. Their degradation meant that the plants might find it harder to gather nutrients from the ocean.

Solé's research sent a shock wave through the scientific community.[84] Seagrass researchers had never thought about noise as a threat. Nor had bioacoustics researchers imagined the possibility that marine plants could be harmed by environmental noise. These findings have enormous implications for marine biodiversity conservation. As offshore operations—from seabed mining to oil and gas and renewable energy construction—are proliferating, little attention has been paid to acoustic effects on marine plant life. While exposure threshold levels have not yet been determined, it is clear that this emerging science will eventually revolutionize the permitting and operations of marine industrial activities. As Solé explains, if every plant and animal in the ocean is sensitive to sound, then noise pollution is not a species-specific issue but rather an ecosystem issue. Michel André says the challenge is now clear:

"Rather than merely imposing thresholds to protect specific species, we have to develop solutions to limit marine environmental noise pollution altogether." This is not welcome news to the global shipping and mining industries. But as André puts it, the scientific bioacoustics community now has regulators "in a boxing ring with their backs against the wall."[85]

André proposes the development of an ecoacoustics index to assess both biological activity and environmental noise pollution impacts.[86] His reasoning is as follows: an area rich in biological activity has a rich and diverse soundscape. A dynamic ecoacoustics index (which monitors the evolution in the soundscape over time) can calculate changing ecosystem health, assessed via changes in acoustic patterns, with greater precision and accuracy than visual methods and at a fraction of the cost.[87] Many ecoacoustics indices already exist. These tend to be computationally intensive; but André argues that the hardware and software are both robust and inexpensive enough to make the incorporation of ecoacoustics indices into environmental monitoring feasible at a global scale. An ecoacoustics index also requires an enormous amount of data to be well calibrated; but André points out that over 150 ecoacoustics observatories around the world have been streaming data continuously, twenty-four hours a day, for over a decade.

If André is correct, a universal ecoacoustics index would be a new standard for environmental health in the twenty-first century.[88] Just as the International System of Units (such as the meter and kilogram) facilitated standardization in commerce and fueled globalization of trade, the invention of a global ecoacoustics index could serve as a precursor to a global system of ecological monitoring, which could be a powerful tool for regulators to combat industrial noise pollution.

Why would we want to invent a global ecoacoustics index, and what purpose would it serve? As André explains, ecosystem health reports could combine data from many different observatories to monitor environmental health, much like weather reports combine data from thousands of rainfall and temperature monitoring stations. In the face of global climate change, we could develop a better understanding of how ecosystems are changing and animals are moving. By archiving each recording, we would also be creating a memory bank of the world's species—a treasure trove for future scientists. But the most important reason to create an ecoacoustics index, André argues, is that environmental noise pollution is not only one of the major threats facing the world, it is one of the few types of pollution we can easily mitigate. Noise is a point-source pollutant, the effects of which decline swiftly once the source is shut down. And unlike increased levels of carbon dioxide or persistent chemicals (which may take decades or centuries to disappear), noise pollution is easy to reverse. The effects are thus immediate and potentially very impactful. Ecoacoustics indices could set thresholds for environmental noise, enabling us to keep noise pollution below hazardous levels. This would benefit humans, too, who suffer from the impacts of environmental noise pollution in the form of stress and increased risks of premature births, heart attacks, cognitive impairment, and dementia.[89]

In marine environments, where creatures are exquisitely sensitive to sound, there are several steps we can take to reduce noise pollution. Changes to shipping can dramatically reduce noise: ships can be routed away from sensitive areas, reduce their speeds, and be designed with quieter propellers and engines. Seismic marine guns could be banned; other types of exploration devices could be used in their place. Until recently, reducing ocean noise was a seemingly fanciful daydream. In 2011, a group of scientists made a quixotic suggestion: halt marine shipping for a year, in order to study the ocean in the absence of human noise.[90] It would be, as oceanographer Peter Tyack poetically declared, "a never-before glimpse of the ocean with little human interference . . . like looking at the night sky if most of the world's lights were turned off."[91] The idea inspired another group of scientists to publish a plan for how to conduct the International Quiet Ocean Experiment—which would last only for a few hours—should the opportunity ever arise.[92] Even that idea seemed out of reach.

Then, COVID hit. As global shipping abruptly halted, researchers documented a massive decline in noise pollution on land and across the world's oceans.[93] In some regions, like the coast of the Pacific Northwest in North America, the seas had not been this quiet for decades.[94] The pandemic slowdown was a Quiet Ocean Experiment come to life, and it showed just how quickly the Earth might benefit from a reduction in environmental noise.[95] The pandemic lockdown was a poignant reminder of how much we have lost as we have drowned out the Earth's soundscapes, and how much the planet has to gain if we choose to quiet ourselves and begin listening again.

Breaking the Earth's Beat

Even if we manage to reduce noise pollution, the Earth's soundscapes are facing another serious threat: climate change. Although humans are still largely oblivious, climate change is directly altering the Earth's natural soundscapes. Sound-sensitive organisms, both marine and terrestrial, are experiencing destabilizing shifts in their acoustic habitats. Three of the world's leading acoustic scientists—Jérôme Sueur, Bernie Krause, and Almo Farina—have described climate change as literally "breaking the Earth's beat": rupturing the sonic rhythms of life, both biophony (the sounds made by animals, plants, and insects) and geophony (sounds coming from rain, water, wind, and the Earth itself).[96]

How is this happening? As weather and ocean conditions change, the patterns of sound transmission in the environment also change, because sound speed varies with temperature, humidity, wind, and even rain intensity. In a warming world, with more extreme weather events, the range of communication between individual organisms can dramatically change; sounds might transmit less far, limiting the ability of animals to communicate, socialize, mate, and even find one another. Or it might require more energy to communicate, hampering their ability to survive.

Ambient temperature also directly influences the vocalizations and hearing processes of many species, from birds and insects to amphibians, fish, and crustaceans. For instance, the rate, pitch, and volume at which amphibians, fish, and arthropods vocalize are temperature dependent—recall the discussion in chapter 7 of Pierce's experiments at Harvard that revealed that crickets chirp at a rate proportional to ambient air temperature. Climate change also affects the patterns of cyclical and seasonal natural phenomena, including acoustic phenomena, which play such an important role in both ecology and evolution. Climate change induces shifts in these seasonal acoustic patterns either by affecting organisms directly or by affecting the resources on which they depend (such as food). If copepods disappear from large swathes of the warming ocean, whales may no longer come there to sing.

As temperatures change, the cicadas and the crickets, the frogs and the fish may change their songs or even cease singing. According to one group of scientists, the long-term effects of changing oceans may result in "silent winters and rock-and-roll summers," as fish cease their choruses in response to winter storms of greater frequency and intensity.[97] These acoustic changes are likely to have the most dramatic impacts on tropical species, which have a low tolerance for heat changes and a limited ability to acclimate.[98]

Even the furthest reaches of the planet are likely to be affected, including the Arctic and Antarctica. Using autonomous recording devices placed in Alaska's remote Brooks Range, a team of researchers led by Ruth Oliver at Columbia University monitored the arrival times and vocalizations of migratory avian species at traditional breeding grounds.[99] In contrast to bird-tagging studies, which are laborious and cover only a small fraction of the birds, the recording devices generated data on region-scale changes in the migratory timing of the birds over five consecutive years. Using machine learning methods borrowed from human speech recognition software, the researchers found that environmental conditions influenced not only arrival dates but also songbird vocal activity, particularly before the birds began laying their eggs. Just like birdsong patterns are changing, the habits of many other species are changing.

As Sueur and his colleagues write, changing thermal and moisture conditions are "detuning" natural sounds—much like a musical instrument might become out of tune.[100] As the planet's atmosphere changes, the Earth's weather and geological soundscapes are evolving as cyclones and tornadoes, floods and wildfires, heat waves and droughts intensify. As climate change warps soundscapes, nature's sounds become more difficult to recognize and harder to hear, or even disappear altogether. The natural sounds that cue animals' behaviors—mating, migration, habitat choice—are different, disoriented, absent. Climate change–induced acoustic transformation thus poses a significant threat to species around the world. Mitigating climate change is already an urgent agenda; the realization that climate change is a source of sonic disturbance provides yet another reason to act. This is an urgent issue; as biosemiotician Gregory Bateson once observed, any widespread ecosystem collapse is likely to be preceded by a collapse in nature's communicative order and a dwindling of nature's chorus.[101] On a global scale, noise pollution may be as significant an ecological threat as chemical pollution.

In 2017, UNESCO introduced a resolution on the importance of sound in today's world, which proclaims "the sound environment is a key component in the equilibrium of all human beings in their relationship with others and with the world."[102] Few governments have acted, although the European Union's Marine Strategy Framework Directive mandates that European Union member states monitor and mitigate noise pollution. Given the accumulating weight of scientific evidence, similar legislative changes are likely to follow.[103] If so, bioacoustics technologies, and expanded environmental noise pollution standards, may one day become the norm in environmental regulation worldwide.

But Michel André believes that these technologies are not merely a tool for regulators. As he puts it: "Thanks to digital technologies, we have developed a new sense—like a sixth sense—of being able to listen to the environment. We can listen to the ocean just like a dolphin or a whale. But even better than a dolphin or a whale, as we have the capacity to listen everywhere, at the same time, all the time. Ultimately, this insight should help us reconnect with nature, to recover something that we had lost." These are not new discoveries, he adds. "When we work in the Amazon, we hear many mysterious sounds through our microphones. We can record them, but we don't understand them. Local communities are able to explain these sounds to us; living in place, they have the wisdom and knowledge to identify the sounds, and understand their ecological context." [104] While advocating for a universal ecoacoustics index to inform environmental assessment and regulation, André warns of the need for humility about the limits of science; although we should avoid recolonizing and appropriating Indigenous knowledge, we have much to learn and relearn from traditional knowledge.

Without place-based knowledge, ecoacoustics is merely an accounting exercise: counting sounds without understanding them. Only by combining digital listening with deep listening—to living communities of organisms in specific places—will we achieve understanding of the meaning of the sounds around us. And only when we understand the meaning of the sounds will we be motivated to protect the organisms that make them. This is why scientists are now implementing acoustics monitoring systems around the world, from the depths of the ocean to the deepest reaches of the world's remaining frontier forests.[105] Alice Eldridge, a musician and data scientist, imagines a future where such bioacoustics networks incorporate acoustic early warning signals; not merely documenting the Earth's demise, but triggering action before it is too late.[106] She also echoes calls of Indigenous leaders to preserve Earth's natural soundscapes, citing the words of a Kichwa elder: "The set of songs heard is like a symphony, which took millions of years to write. It is a unique and priceless creation, which we cannot let be destroyed or disappear."[107]

A Sonic Microscope

We are just beginning to understand the universal importance of sound for species across the full range of the Tree of Life. From the humble coral to the mighty whale, the nonhuman world is more sensitive to sound than we suspected. Many nonhuman creatures use sound to communicate with one another, in much more complex ways than scientists previously understood. By using digital bioacoustics tools, we can record these complex forms of communication; by using artificial intelligence, we can decode them.

Bioacoustics and artificial intelligence, combined, offer humanity a powerful new window into the world of nonhuman meaning-making. You and I could never sing like a whale or buzz like a bee, but computers and biomimetic robots can. Our digital devices have brought us to the brink of a new era in digitally mediated interspecies communication.

This could transform not only environmental conservation but also our understanding of nature, and what it means to be human. How might we choose to live on this planet when the voices of creation are (once again) both audible and meaningful to us?

To appreciate just how far-reaching these shifts in thinking might turn out to be, consider the impact of another revolutionary technology, several centuries ago: the microscope. As historian Catherine Wilson argues, the microscope was a foundational catalyst of the Scientific Revolution, transforming both scientific practice and humanity's wider view of its own importance and relationship with the living world.[108] Bioacoustics is poised to alter humanity's relationship with our planet to a similar degree, but through expanding our sense of sound rather than our sense of sight.

When first brought to scientific prominence by Anton van Leeuwenhoek, a Dutch fabric merchant with a grade school education, the implications of the microscope were not immediately apparent. Van Leeuwenhoek's genius lay not only in building microscopes—he built over five hundred of them, many of which achieved unprecedented resolution—but also in his quirky habit: inspecting the mundane world. Whereas Galileo gazed at the heavens, van Leeuwenhoek gazed at well water, mold, lice, yeast, blood cells, human breast milk (his wife's), and sperm (his own). When he put his eye to his homemade glass lenses, he saw something astounding: animalcules—microscopic organisms endlessly varied in shape and size—danced and wriggled across the view frame. The world was literally alive with tiny, wriggling, fantastical creatures whose existence humanity had not even suspected.

Confronted with this strangeness, Van Leeuwenhoek initially kept his discoveries secret for fear of ridicule. Eventually, he penned a letter to the Royal Society in London—the leading scientific society of the time.[109] The Society's fellows initially viewed his discoveries with skepticism, proving the maxim that humans tend to believe that whatever they cannot perceive does not exist. But van Leeuwenhoek insisted: magnification revealed a strange new world of beings, living in every nook and cranny of our world, unseen by the unaided eye.[110] Spectacles helped us focus on the written word; telescopes brought the starry heavens closer; but the microscope opened up entirely new, hitherto unimagined worlds. After sending out a delegation to inspect the microscopes, the Royal Society eventually accepted his findings.[111] Van Leeuwenhoek's research papers were published alongside those of Sir Isaac Newton in the leading scientific journal of the day.[112]

As microscopes proliferated, they created new possibilities for scientists and philosophers alike, renewing interest in theories like atomism and mechanism. The exploration of the microscopic world—and the growing realization of the role of animalcules in both generating life and spreading contagion and disease—intrigued and influenced philosophers like Bacon, Descartes, and Locke. When the microscope revealed the existence of pathogens, commonly held ideas about disease (such as the theory that illness was caused by bad odors or sin) were cast into doubt, and then cast aside. Van Leeuwenhoek's use of microscopes as visual prosthetics—artificial eyes that helped humanity see new things in new ways—laid the foundation for countless future breakthrough discoveries, including the code of life itself (DNA). The microscope enabled humans to see anew, with both our eyes and our imaginations.

Digital acoustics are an invention of similar significance. Like the microscope, they function like a scientific prosthetic: as they extend our sense of hearing, they expand our perceptual and conceptual horizons. As we encounter new soundscapes around the world and across the Tree of Life, we are learning about the power of sound to convey information and meaning, but also to harm and injure. In the meantime, we are learning how to use our newfound knowledge to better protect planet Earth.

Just like van Leeuwenhoek peering through his newly built microscope, we do not yet understand everything brought to light by this new digital acoustics technology. Today, we are hearing things we never imagined we could hear. This is by no means novel (Indigenous traditions offer powerful ways of nonhuman listening) or neutral (digital technologies can be misused and abused). But with caveats and safeguards, bioacoustics offers humanity a powerful new window into the nonhuman world. Through bioacoustics, we are learning about the universality of meaning-making through sound, by all beings in creation. Aided by artificial intelligence, we may be on the verge of a breakthrough in interspecies communication. If we open our ears, a world of wonders awaits.

1. Pershing et al. (2015).

2. Record et al. (2019).

3. Clark et al. (2010); Davis et al. (2017, 2020); Grieve et al. (2017); Meyer-Gutbrod and Greene (2018); Meyer-Gutbrod et al. (2018); Record et al. (2019); Scales et al. (2014); Simard et al. (2019); Woodson and Litvin (2015).

4. Almén et al. (2014); Grieve et al. (2017); Wishner et al. (2020).

5. MacKenzie et al. (2014).

6. Stokstad (2017).

7. Whale mortality statistics are gathered separately on the US and Canadian sides of the border; the total observed mortality, due to shipping and fishing, of North American right whales in 2017 was estimated at 4 percent of the population: Davies and Brillant (2019); Daoust et al. (2017); Johnson et al. (2021); Koubrak et al. (2021); Sharp et al. (2019).

8. Davies and Brillant (2019); Department of Fisheries and Oceans (2017).

9. Gavrilchuk et al. (2021). See also Williams (2019).

10. Davies and Brillant (2019).

11. Detailed statistics on North Atlantic right whale mortalities are kept by NOAA: https://www.fisheries.noaa.gov/national/marine-life-distress/2017-2021-north-atlantic-right-whale-unusual-mortality-event.

12. Parks et al. (2011).

13. Davis et al. (2020).

14. CBC News (2020). See also Gervaise et al. (2021).

15. Government of Canada (2021a).

16. Government of Canada (2021b).

17. Subsection 38(1) of the Canada Shipping Act allows for fines of up to $1 million or a prison term not exceeding eighteen months (or both) for violations of a regulation that implements Canada's international obligations: Koubrak et al. (2021).

18. All fishers and harvesters using ropes are also required to use only weak ropes in fixed-gear fishing, so that ropes can break to help whales self-release if they become entangled. A major "ghost gear" initiative has been launched to fund the recovery of lost nets, ropes, and lines, which also pose a major threat to the whales.

19. Durette-Morin et al. (2019). See also http://whalemap.ocean.dal.ca/.

20. Lostanlen et al. (2021).

21. Carnarius (2018); International Chamber of Shipping (2020).

22. Channel Islands National Marine Sanctuary (n.d.).

23. Morgan Visalli, interview with author, November 2020; see also Visalli et al. (2020).

24. Olson (2020).

25. Similar systems have already been used with some success for right whales in the North Atlantic: National Geographic (2020); NOAA Fisheries (2020a, 2020b); Nrwbuoys.org (2020).

26. Baumgartner et al. (2019).

27. Abrahms et al. (2019).

28. Whale Safe's acoustic data is continuously monitored, and updates are sent every two hours. Visual data is sourced via Whale Alert (a citizen science app, with more activity at peak whale watching, tourist, and recreational boater seasons) and Spotter Pro (an app used by professional naturalists and scientists). Modeling data on oceanographic conditions favoring whales is updated daily. Ship position data is updated daily, with a two- to three-day lag.

29. Fox (2020); Olson (2020); Simon (2020).

30. See http://www.whalealert.org.

31. CBC News (2019); Jeffrey-Wilensky (2019); Lubofsky (2019); Murray (2019).

32. Davies (2019); Durette-Morin et al. (2019).

33. Barlow and Torres (2021); Barlow et al. (2018, 2020, 2021); Torres (2013); Torres et al. (2020).

34. New Zealand Supreme Court (2021).

35. Barlow and Torres (2021).

36. Lavery et al. (2010); Pershing et al. (2010); Roman et al. (2014).

37. Chami et al. (2019).

38. IPCC (2019).

39. Poloczanska (2018).

40. Abecasis et al. (2018); Cooke et al. (2011); Cowley et al. (2017); Currier et al. (2015); Haver et al. (2018); Steckenreuter et al. (2017).

41. Proulx et al. (2019).

42. Jones et al. (2020); McWhinnie et al. (2018); Siders et al. (2016).

43. Cooke et al. (2017); Hays et al. (2016); Wilmers et al. (2015).

44. Our ability to watch and listen to animals in places that we could not reach in the past has given rise to new bioacoustics methods in the field of movement ecology—a scientific discipline dedicated to understanding the movements of organisms across space and time. See Nathan et al. (2008) and Fraser et al. (2018).

45. Chalmers et al. (2021); Dodgin et al. (2020).

46. Burke et al. (2012).

47. Braulik et al. (2017); Showen et al. (2018); Woodman et al. (2003, 2004). See also Gibb et al. (2019).

48. Culik et al. (2017); Curé et al. (2013); Omeyer et al. (2020).

49. See, for example, Todd et al. (2019).

50. Clark et al. (2009).

51. Chou et al. (2021).

52. Lindsay (2012).

53. Erbe et al. (2019).

54. Boyd et al. (2011).

55. Duarte et al. (2021).

56. Rolland et al. (2012).

57. Jariwala et al. (2017); Passchier-Vermier and Passchier (2000).

58. Despite the findings, the federal government authorized permits for oil and gas exploration companies to use seismic noise cannons to map the ocean floor off the east coast, in preparation for possible drilling. See Struck (2014).

59. Jones et al. (2020).

60. Charifi et al. (2017); Erbe et al. (2018); Kaifu et al. (2007).

61. de Soto et al. (2013); Hawkins et al. (2015); McCauley et al. (2003); Popper and Hastings (2009); Richardson et al. (1995).

62. Fewtrell and McCauley (2012); Kostyuchenko (1971); McCauley et al. (2017); Neo et al. (2015); Pearson et al. (1992).

63. Di Franco et al. (2020); Dwyer and Orgill (2020); Erbe et al. (2018); Kavanagh et al. (2019).

64. Francis and Barber (2013); Kight and Swaddle (2011); McGregor et al. (2013).

64. Francis and Barber (2013); Kight and Swaddle (2011); McGregor et al. (2013).

65. For a metareview, see Barber et al. (2010) and Duquette et al. (2021).

66. This is known as the Lombard effect. See, for example, Brown et al. (2021).

67. Gomes et al. (2021).

68. Cinto Mejia et al. (2019); McClure et al. (2013, 2017); Ware et al. (2015). Similar results have been found with "phantom gas fields" (recorders that play the sounds of compressors and other machinery used in natural gas extraction)—a concern given that six hundred thousand new gas wells have been drilled across North America in the past twenty years.

69. Barber et al. (2011); Buxton et al. (2017).

70. Mariette et al. (2021). See also Nedelec et al. (2014) and Rivera et al. (2018).

71. Jain-Schlaepfer et al. (2018).

72. Buehler (2019). See also Fakan and McCormick (2019).

73. Boudouresque et al. (2006, 2016); Hemminga and Duarte (2000); Lamb et al. (2017); UNEP (2020).

74. Boudouresque et al. (2009); Capó et al. (2020); Edwards (2021); Green et al. (2021); Jordà et al. (2012); Krause-Jensen et al. (2021).

75. André et al. (2011); Solé et al. (2013a, 2013b, 2016, 2017, 2018, 2019, 2021a, 2021b).

76. den Hartog (1970).

77. Arnaud-Haond et al. (2012).

78. Statocysts enable orientation, balance, sound detection, and gravity perception in marine organisms. They function in a manner similar to inner ear organs in fish, which detect particle motion and pressure in water. In cephalopods, which do not have ears, statocysts are located within the cephalic cartilage. Early stages of cephalopods present sensory hair cells grouped into lateral lines on their heads and arms. This explains how, even without ears, octopuses can locate prey or predators, particularly in low light conditions; with their statocysts and multiple arms lined with sensory hair cells, they sense even tiny sounds through vibrations in the water.

79. Two types of noise frequencies were used: scanning and transmission electron microscopy techniques. See Solé et al. (2013b).

80. Solé et al. (2018).

81. Solé et al. (2021a).

82. Amyloplasts are starch-filled plastids that orient the plant in the water column, much like sound-sensitive statocysts help marine invertebrates orient in space. Amyloplasts, somewhat like mitochondria in our cells, are separate organelles that are surrounded by a double-lipid membrane, and that possess their own DNA. As they produce and store starch inside the internal membrane compartments, amyloplasts sediment within cells; as they do so, they trigger gravity signal transduction in the plant (sending a message to specific parts of the root, allowing it to direct itself downward). See Solé et al. (2021a). See also Hashiguchi et al. (2013); Kuo (1978); Pozueta-Romero et al. (1991); and Yoder et al. (2001).

83. Solé et al. (2021a).

84. Solé et al. (2021a).

85. Michel André and Marta Solé, interview with author, October 2021.

86. An ecoacoustics index is a mathematical function that synthesizes key aspects of acoustic energy in an "auditory scene." Indices can adopt a variety of methods, such as calculating the signal-to-noise ratio or the spectral distribution of energy, or segmenting the data into patterns associated with acoustic events: Barchiesi et al. (2015); Kholghi et al. (2018).

87. An ecoacoustics index is a dynamic measure; because the Earth is balanced dynamically,

87. An ecoacoustics index is a dynamic measure; because the Earth is balanced dynamically, forever evolving in space and time, ecoacoustics indices also evolve dynamically.

88. See, for example, Bohnenstiehl et al. (2018).

89. Barzegar et al. (2015); Basner et al. (2017); Bates et al. (2020); Cantuaria et al. (2021); Dutheil et al. (2020); Thompson et al. (2020).

90. Boyd et al. (2011).

91. Tamman (2020).

92. For more on the International Quiet Ocean Experiment (or IQOE), see https://www.iqoe.org/. See also Tamman (2020).

93. Basan et al. (2021); Denolle and Nissen-Meyer (2020); Derryberry et al. (2020); March et al. (2021); Nuessly et al. (2021).

94. Čurović et al. (2021); see also Coll (2020); Cooke et al. (2021); Ryan et al. (2021).

95. Asensio, Aumond, et al. (2020); Asensio, Pavón, et al. (2020); Lecocq et al. (2020); Silva-Rodríguez et al. (2021); Vishnu Radhan (2020).

96. Sueur et al. (2019).

97. Siddagangaiah et al. (2021).

98. Burivalova et al. (2019); Chen et al. (2011); Francis et al. (2017); Gibbs and Bresich (2001); Larom et al. (1997); Narins and Meenderink (2014); Oliver et al. (2018); Parmesan and Yohe (2003); Sugai et al. (2019).

99. Oliver et al. (2018).

100. Sueur et al. (2019). See also Krause and Farina (2016).

101. Harries-Jones (2009).

102. UNESCO (2017).

103. Chou et al. (2021); Duarte et al. (2021).

104. Michel André and Marta Solé, interview with author, October 2021.

105. See, for example, Williams et al. (2018); Zwart et al. (2014).

106. Eldridge (2021).

107. Eldridge (2021, 4).

108. Wilson (1997).

109. Coghlan (2015).

110. Poppick (2017).

111. Royal Society (n.d.).

112. Ford (2001).

Published by Princeton University Press
41 William Street, Princeton, New Jersey 08540
99 Banbury Road, Oxford OX2 6JX

press.princeton.edu

ISBN 9780691206288
ISBN (e-book) 9780691240985

British Library Cataloging-in-Publication Data is available

Editorial: Alison Kalett and Hallie Schaeffer
Production Editorial: Natalie Baan
Text Design: Karl Spurzem
Jacket/Cover Design: Amanda Weiss
Production: Jacquie Poirier
Publicity: Kate Farquhar-Thomson and Sara Henning-Stout
Copyeditor: Jennifer McClain

Jacket images from top to bottom: European pond turtle from *Deutschlands Amphibien und Reptilien* by Bruno Dürigen, 1809. “Bees and Lilies,” illustration from *Stories of Insect Life* by William J. Claxton, 1912, Private Collection / Bridgeman Images. “Group of Corals,” illustration from *Science for All* by Robert Brown, 1877. *Patulous gorgonia* or Flat Gorgonia illustration from *The Naturalist’s Miscellany* (1789–1813) by George Shaw. Medical botany plant / Raw Pixel. Tomato plant, 1649–1659, Hans-Simon Holtzbecker. Soundwave by Marina / Adobe Stock.

This book has been composed in Arno

Printed on acid-free paper. ∞

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

notes:

ily cere- cahiers is a collection of texts(fragments). it is a branch of the collective *it is part of an ensemble*. these texts function as starting points for dialogues within our practice. we also love to share them with guests and visitors of our projects.

the first copy of *ily cere- cahier 33* was printed in september 2025

www.ilycere-cahiers.com
www.blyisnokino.com
www.itispartofanensemble.com
www.peelrealoynoun.com
www.naipattaofficial.com
www.onarynornotice.com