TRACEY JENNINGS

A diverse array of marine life fills the waters that surround Raja Ampat, Indonesia.

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SEA CHANGE

The increasing acidity of our seas is a threat to marine life that for many species may be impossible to overcome.

BY SARAH DEWEERDT

Female shore crabs are diligent mothers. They produce around 100,000 eggs at a time, which they hold as an orange–brown mass on the underside of their abdomen, using leg-like appendages known as pleopods to pump water over the eggs to ensure a steady flow of oxygen as the young inside develop.

At least, that's what happens in normal sea water, which has a pH of about 8.1. If the pH falls to 7.7 or so — conditions that could arise in the oceans by the end of the century, owing to the anthropogenic release of carbon dioxide (CO_2) into the atmosphere — the shore crabs (*Carcinus maenas*) don't tend their eggs. "They just doze," says Jörg Hardege, a chemical ecologist at the University of Hull, UK.

The reason, Hardege and his colleagues reported[1] in 2016, is that the more acidic water alters the shape and electric charge of a molecule, released by the eggs, that stimulates the female crab to pump water. She can no longer recognize the molecular signal, and therefore neglects her eggs.

The shore crab's lazy mothering is just one of a rapidly expanding set of biological effects that researchers are documenting in the oceans — involving organisms that range from the single-celled phytoplankton at the base of the marine food web to the fish at its peak — that could stem from the ongoing decrease in the pH of sea water.

Not all species are equally vulnerable to this acidification of the oceans, a fact that has the potential to restructure marine ecosystems. More broadly, as well as scrambling signals used in communication, changes to ocean chemistry in the coming decades could dissolve the skeletons of marine organisms, deplete the energy reserves of such organisms and even interfere with the function of their nervous systems.

ACID TEST

As the burning of fossil fuels increases the concentration of atmospheric CO_2, the amount of CO_2 dissolved in sea water increases in tandem. The oceans are Earth's largest carbon sink — by some estimates, about 40% of anthropogenic CO_2 has been absorbed by the seas.

Some of that extra dissolved CO_2 reacts with molecules of water in a series of reactions that leads to the formation of carbonic acid, and bicarbonate and hydrogen ions (see 'Ocean impact'). The greater the concentration of hydrogen ions, the lower the pH of the water will be and the more acidic the conditions.

At the start of the Industrial Revolution, the global average ocean pH was about 8.2 — around 0.1 units higher than it is today. That may not seem like a big difference, but a similar decrease in the blood pH of humans can lead to dire consequences, including seizures, heart arrhythmia and coma. Because pH is measured on a logarithmic scale, every change of 0.1 units results in a 26% increase in concentration of hydrogen ions.

"If you think about the enormous scale of the oceans, it's a tremendous amount of CO_2 that the oceans have taken up" to yield even such a small shift in global average pH, says George Waldbusser, an ecologist at Oregon State University in Corvallis.

Further change is likely to come. If carbon emissions continue at the present rate, the global average ocean pH will probably fall to around 7.7 by 2100. And even if nations drastically curtail emissions to meet their commitments under the 2015 Paris climate agreement, the pH of the oceans will still be about 7.9 at the century's end.

Moreover, after CO_2 has dissolved in sea water, it can stay there for a long time, even if its concentration in the atmosphere decreases, owing to patterns of circulation that cause surface water to sink deep into the oceans. "What we do in the next few decades will impact the oceans for tens of thousands of years," says Carol Turley, a biogeochemist at Plymouth Marine Laboratory, UK.

SHELL SHOCK

An understanding of ocean acidification and its biological effects was slow to emerge, especially compared with that of the increase in global temperature caused by rising levels of atmospheric CO_2. The Intergovernmental Panel on Climate Change didn't mention ocean acidification in its reports until 2007. Most research on the topic has unfolded in the past 20 years.

Initial concern, and still probably best known to the public, focused on calcifiers — a diverse group of marine organisms that make shells or skeletons from calcium carbonate. A 1998 study[2] suggested that increased levels of CO_2 in sea water could hamper calcification by reef-building corals in tropical waters. In 2000, coccolithophores — single-celled algae that build striking shells from overlapping plates of calcium carbonate — were reported[3] to form their shells more slowly when exposed to water high in dissolved CO_2.

Ocean acidification interferes with shell formation because hydrogen ions in sea water react with carbonate ions, forming bicarbonate ions. More-acidic sea water means that there will be fewer carbonate ions to incorporate into calcium carbonate, and therefore less raw material for building shells. Waldbusser and colleagues have found that in waters undersaturated with carbonate, the larvae of bivalves such as clams and oysters have trouble starting their shells, which form more slowly or turn

A bloom of bioluminescent dinoflagellates in Vieques, Puerto Rico.

The shells of sea snails can dissolve in acidified water.

LEFT: DAVID LITTSCHWAGER/GETTY IMAGES; RIGHT: NINA BEDNARSEK, NOAA

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MIKE PARK, UNIVERSITY OF HULL

A female shore crab (*Carcinus maenas*) tends to her eggs.

out misshapen. Such effects are thought to explain why shellfish hatcheries on the west coast of the United States are struggling, Waldbusser says.

Stronger evidence for the perils of acidic oceans comes from a 2016 study[4] in which the chemistry of the water around small portions of the Great Barrier Reef in Australia was returned to that of before the Industrial Revolution. The corals in those areas grew about 7% faster than elsewhere on the reef. "That was an extraordinary experiment because it actually showed that [ocean acidification is] already having an impact," Turley says.

As well as affecting the formation of skeletons and shells, acidic sea water can cause shells to dissolve. For most species, difficulties in shell formation will happen at a much lower threshold of acidity than shell dissolution. But pteropods — tiny, free-swimming sea snails that are an important component at the base of the food chain — seem to be especially vulnerable to the corrosive effects of acidic water. A 2014 study[5] found that more than half of the pteropods collected from waters off the US west coast had severely dissolved shells.

ENERGY DEMANDS

When carbonate is scarcer, organisms have to expend more energy to gather material for their shells. As research into ocean acidification has accelerated in the past decade, it has emerged that many of its other biological effects also boil down to energy imbalances.

"The basic problem is the same for all marine organisms," says Felix Mark, a marine ecophysiologist at the Alfred Wegener Institute in Bremerhaven, Germany. Many organisms have mechanisms to regulate internal pH, such as pumping hydrogen ions in or out. As the pH of sea water falls, organisms have to work harder to keep their own pH constant. "It's going to cost you energy. As simple as that," says Mark.

Mark and colleagues have found that the energy strain imposed by ocean acidification can particularly affect young fish, which otherwise tend to put all their resources into growth. In laboratory experiments, Mark's group has shown that at concentrations of dissolved CO_2 expected by the end of the century, the larvae of some species of fish, including the Atlantic herring (*Clupea harengus*), show slower growth and higher mortality.

Other forms of ocean life, however, may find that their energy budget actually benefits from such shifts in ocean chemistry. For example, as the concentration of dissolved CO_2 increases, phytoplankton won't have to work as hard to get the CO_2 they use to produce energy through photosynthesis.

ACIDIC SEA WATER CAN CAUSE SHELLS TO DISSOLVE.

On the face of it, creating a more robust base for the ocean food web through these algae sounds like good news, but there are downsides. Boosting algal growth can cause depletion of oxygen in the water when those extra cells die and are broken down by bacteria, creating conditions that can be lethal to fish and disrupting the cycling of nutrients through the food chain. Moreover, the species that benefit most from this 'fertilization' by CO_2 may be harmful to people. Increased levels of CO_2 in the oceans could worsen blooms of toxic algae such as dinoflagellates, says David Hutchins, a phytoplankton biologist at the University of Southern California in Los Angeles. "One of the things that they do, these harmful bloom species, is use that extra carbon to make toxins. They make quite a bit more toxin under high CO_2," he says.

SENSE OF SMELL

The blockage of molecular signalling due to ocean acidification that Hardege and colleagues documented in the shore crab could affect many more species. The same molecule that triggers egg-tending behaviour in female shore crabs also guides the settlement of oyster larvae and the hermit crab's hunt for a shell, meaning that those behaviours

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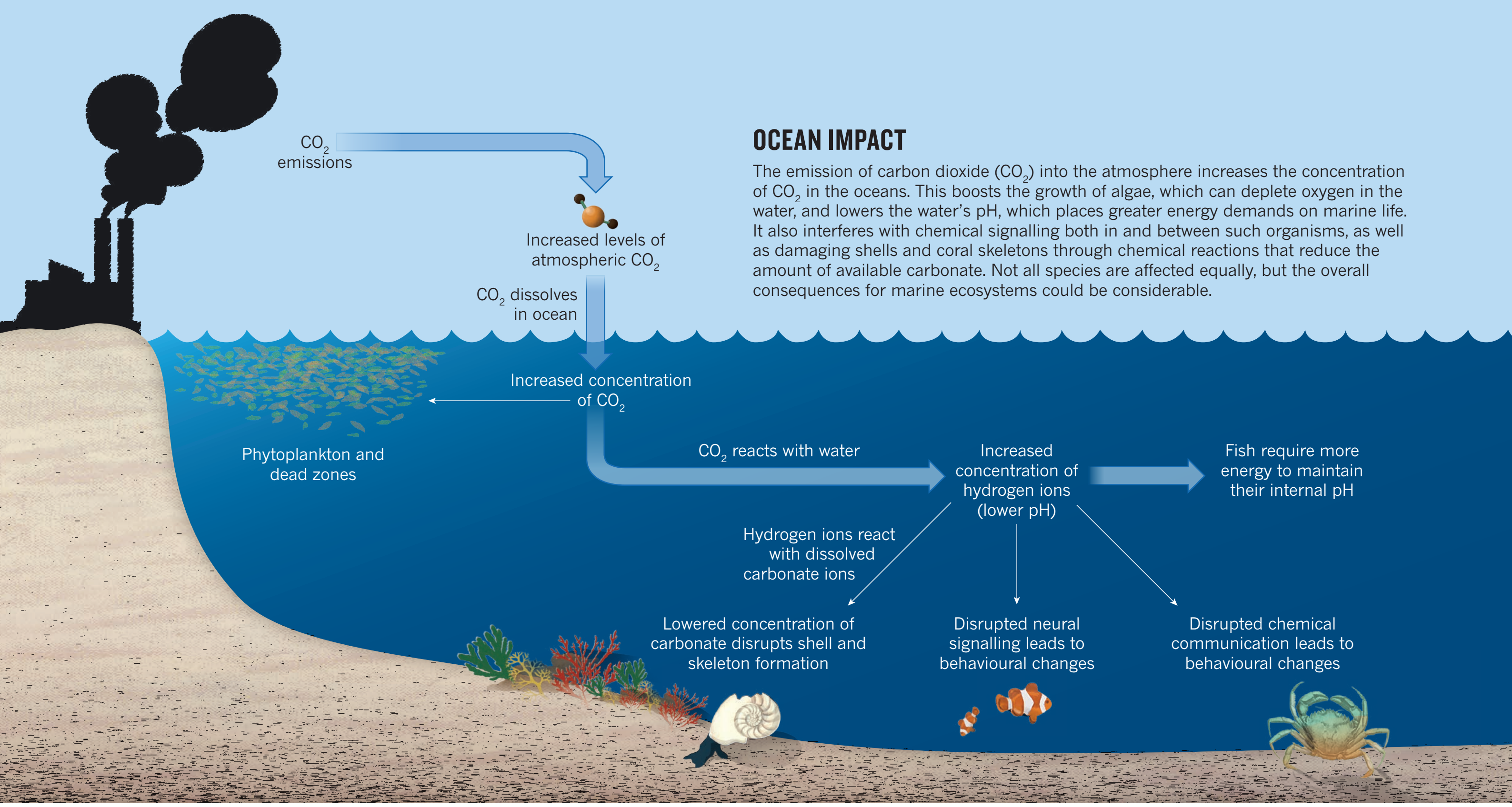

could be similarly susceptible to disruption by acidification.

The oceans are thought to be awash with signalling molecules. Chemical communication — essentially, the sense of smell — is one of the earliest forms of biological communication, and marine organisms use it to attract mates, find food, detect and avoid predators, and decide on a place in which to live.

> "THE BASIC PROBLEM IS THE SAME FOR ALL MARINE ORGANISMS."

The specific shape and charge of signalling molecules enables them to interact with the sensory receptors of animals, similar to a key in a lock. But such properties are altered as the pH changes. The pH at which these shifts occur varies for different molecules, but for many of those on which animals rely for chemical communication, the tipping point is around pH 8.0, rendering the molecules vulnerable to present or near-future ocean acidification.

Acidification not only disrupts signals sent between organisms. It also wreaks havoc on those transmitted internally — specifically, the nerve impulses that enable animals to process and react to the environment. These effects were initially documented in orange clownfish (*Amphiprion percule*), which live among reef-building corals. When placed in water that is high in dissolved CO_2, clownfish become less likely to swim away from the scent of a predator. Some species of damselfish, which also inhabit tropical reefs, also fail to freeze and hide when exposed to the scent of an injured fish — a stimulus that usually serves to warn of predators. When damselfish that had been held in water similarly high in CO_2 were subsequently placed on experimental reefs in the natural environment, "they had high mortality, and that was likely because they were attacked by predators," says Philip Munday, an ecologist at James Cook University in Australia.

Further studies, in collaboration with Göran Nilsson at the University of Oslo, suggested that these effects occur because efforts by fish to stabilize body pH in acidified water alter their blood chemistry in a way that interferes with signalling by the neurotransmitter GABA (γ-aminobutyric acid).

A similar mechanism affects invertebrate behaviour. The humpbacked conch (*Gibberulus gibberulus*), a species of sea snail with a modified foot that it uses to leap away from predators, is at a disadvantage when exposed to acidified water. The snails are less likely to execute their characteristic evasive hop and, when they do, they are less likely to jump in the correct direction. This effect can be reversed by a drug that blocks a receptor for GABA, confirming the mechanism involved.

Meanwhile, the humpbacked conch's main predator, the marbled cone snail (*Conus marmoreus*) — a slow-moving mollusc that shoots an envenomed dart to catch prey — is less effective at hunting in acidified water. This study of the dynamics between two snail species is emblematic of the next steps in research on ocean acidification. Having amassed evidence about the possible effects of acidification on many species, Munday and other researchers say that what's needed now is an understanding of how interactions between species and the shape of marine food webs might change.

Studies will also need to take into account that more than one stress — including warming, deoxygenation and acidification — affects the oceans at the same time. And researchers must ask what is perhaps the ultimate question: what can organisms do to cope? "One problem with all these sorts of experiments that we've been doing is that we basically teleport this animal into the future," Munday says. But instead of abruptly transferring organisms from current conditions to those high in CO_2, researchers need to test whether organisms will be able to adapt as ocean acidification proceeds in the coming decades — a time frame that amounts to thousands of generations for some, but just a handful for others.

Experiments with fast-reproducing organisms such as phytoplankton are beginning to provide insight into these questions. For longer-lived species, genetic analysis might help to predict their ability to adapt to future conditions. But it will be tricky to find answers before our large-scale planetary experiment in ocean acidification has run its course. ■

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1. Roggatz, C. C., Lorch, M., Hardege, J. D. & Benoit, D. M. *Glob. Chang. Biol.* **22,** 3914–3926 (2016).
2. Gattusoa, J.-P., Frankignoulleb, M., Bourgeb, I., Romainea, S. & Buddemeierc, R.W. *Global Planet. Change* **18,** 37–46 (1998).
3. Riebesell, U. *et al. Nature* **407,** 364–367 (2000).
4. Albright, R. *et al. Nature* **531,** 362–365 (2016).
5. Bednaršek, N. *et al. Proc. Biol. Sci.* **281,** 20140123 (2014).

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