Marine viruses changing Earth's system: study

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Melissa Duhaime (left), a postdoctoral fellow with Matthew Sullivan's group, extracts viruses from water samples taken from the Ocean Biome in the UA's Biosphere 2, together with lab technician Nina Gregory. The researchers take advantage of the Biosphere 2 Ocean to develop new ways to visualize and study microbial and viral interactions in the wild.

All but overlooked until the past decade, marine viruses far outnumber any other biological entity on the planet. Scientists are only beginning to discover the invisible particles that are the cogs of Earth's system, changing dynamics in food webs, fisheries, even climate.

In his lab in the University of Arizona's Life Sciences South Building, Matthew Sullivan opens the door of an incubator cabinet. Rows of glass flasks crowd the shelves. Their bottoms are covered with liquids shimmering in various hues of green; each bears a label for identification. Sullivan takes out one of the flasks and sets it onto a lab bench.

"The green color comes from microscopically small algae," he says. "We use them to culture the viruses. These microbes serve as their hosts in the wild."

Sullivan's lab just received a $1.6 million research grant from the Gordon and Betty Moore Foundation to "develop and apply novel virus ecology approaches that enable deeper investigations of the structure and activities of natural marine virus communities and the linkages between viruses and their microbial hosts."

In other words, how viruses run the planet by manipulating their microbial hosts.

"Marine viruses are integral cogs of the Earth system," Sullivan says. "The food webs on Earth are fueled by microbes, and microbes in the ocean provide a big chunk of that."

On average, a drop of seawater contains about 10 million viruses, or 10 times as many microbes. These viruses are not the kind that spread around and cause the flu. Instead they infect microbes in the ocean, altering the way they impact ecosystems.

Most biologists do not consider viruses living organisms because they don't feed, grow, have a metabolism and can't reproduce on their own. Instead, they infect host cells, inject their own genetic material and hijack the cell's molecular machinery to make more viruses. In many cases, the viral reproduction cycle kills the host cell, which bursts and releases an army of new virus particles into the environment, ready to infect other cells.

In 2008, Sullivan, an assistant professor with joint appointments in the UA's departments of ecology and evolutionary biology and molecular and cell biology, started the Tucson Marine Phage Lab to study how marine viruses interact with microbes that in turn are drivers of the most fundamental global processes.

Viruses kill marine microbes

"Viruses are only as interesting as their microbial hosts," Sullivan says. "And those are pretty important: they drive the global biogeochemical cycles of carbon, nitrogen, sulfur and oxygen; elements that are crucial for running all kinds of energy conversions on the planet."

"We're learning that enormous numbers of marine viruses are right at the heart of all this," he adds. "They act as a driving evolutionary force of these microbial processes: They kill their host cells, move genes to new hosts, modulate host metabolisms during infection and may even serve as food for their hosts."

"Given the abundance and important roles of viruses in global processes, we ask what kinds of viruses are out there and what they are doing, how they impact the microbes and how they interact with the environment. From our preliminary data we can already say we couldn't have dreamed of all the different interactions, all those biological processes in the oceans that viruses are involved in."

Up to 50 percent of the world's population of marine microbes are turned over each day, killed by viruses, scientists estimate.

"By killing such vast numbers of microbes, the viruses in the wild are probably keeping a lot of energy and carbon from getting into higher levels in the food webs," Sullivan says.

"One can think of carbon as a sort of currency for energy in the Earth system, and 50 percent of that comes from the ocean," Sullivan says. "Only a little over 10 years ago, we thought that number was much lower."

Our planet and all living beings could not survive without the work of vast numbers of invisible organisms inhabiting the ocean waters and the sea floor. Single-celled algae and bacteria known as phytoplankton use energy from sunlight to extract carbon dioxide from the water (and ultimately from the atmosphere) and convert it into organic matter that forms the basis of the food chain. This process is called photosynthesis.

In most textbooks, the food chain starts with the microscopically small algae and cyanobacteria that make nutrients from carbon dioxide and sunlight. Now it turns out there is a whole layer that lies beneath: viruses.

"There are about 10 viruses for every microbe pretty much anywhere you look," Sullivan says. "At this point, we can culture only about 1 percent of microbes in the lab, which means there are 99 percent we really don't know much about. That is where our new methods fit in - finding ways to chase down the other 99 percent."

The greatest challenge to studying viruses is their tiny size. A single-celled alga, undetectable with the naked eye, can accommodate up to several hundreds of virus particles. Researchers must therefore come up with ways to collect viruses from samples and concentrate them and separate them according to their different types.

"Our research is currently in the discovery phase," Sullivan says. "Developing new methods of collecting and identifying viruses makes up a huge part of our work."

With existing methods, scientists were able to extract only a quarter of all the viruses floating in a sample of seawater. Working in the UA's Biosphere 2 Ocean, Sullivan's co-workers recently discovered that by simply adding iron chloride to the water sample, they could trap 95 percent of the viruses in their collecting containers.

Most of the oxygen we breathe is released into Earth's atmosphere by two species of microbes: the cyanobacteria Prochlorococcus and Synechococcus. They are the most abundant photosynthetic cells on the planet and the Sullivan lab is especially interested in studying them and the viruses that infect them.

Viruses provide their hosts with genes

In previous studies, Sullivan discovered something unexpected: The viruses infecting those microbes have genes necessary to build an important part of the photosynthetic machinery used by the microbes to make oxygen.

But why would a virus, a lifeless particle with no metabolism of its own that depends on living microbes to replicate, carry genes it can't use?

"When the virus infects the cell, it shuts down the hosts' ability to do anything," Sullivan explains. "It basically takes over the biochemical machinery and forces the host into making more viruses. It leaves intact only what the cell needs to stay alive and make copies of the virus genome."

To survive, the host depends on its photosynthetic machinery. During photosynthesis, one of the core proteins of this apparatus is subject to such high wear and tear that it needs to be replaced about every 30 minutes.

"The virus has the blueprint for that protein because it will need to replace it once it has taken control of the cell," Sullivan says. "So we discover that viruses directly impact the photosynthetic capacity of their hosts, in addition to killing them and changing their ecology and their evolutionary trajectory."

"Arguably, that is only the tip of the iceberg. That just happens to be the one ocean virus system that has been looked at in any detail."

Marine viruses add a whole new dimension to evolution: It is easy to imagine how a virus takes over genetic material from a host that turns out to be advantageous and transfers it to another microbe during another cycle of infection and virus replication.

"It seems like a good way to speed up molecular evolution," Sullivan says. "The host species could even be using these viruses to jump ahead, to try out new ways to evolve more quickly."

How the ocean is breathing

Sullivan's group expects its discovery-based research to generate knowledge directly applicable to better understand and predict marine ecosystems and fisheries. The scientists focus on viruses from environments on which a lot of information is available.

For example, his team sampled viruses from a so-called oxygen minimum zone in the subarctic Pacific, where vast swaths of ocean contain little or no oxygen at depths from about 500 meters down to 2,000 meters.

"This zone has huge implications for fisheries," Sullivan says, "so scientists have studied it for the past 50 years to find out how the ocean is breathing. We are interested in the interaction between viruses and microbes in that area, but in the context of the physics and chemistry of that important pacific subarctic environment."

Interestingly, one group of marine microbes, named Marine Group A, which is found all over the globe but in extremely low numbers, appears to flourish in the oxygen-depleted waters of oxygen minimum zone where it is found in considerable numbers.

"We don't know anything about them," Sullivan says. "We know it occurs from its genetic ‘footprint' but we can't culture it, so we have no idea what it's doing."

"Oxygen minimum zones in the open ocean are areas where microbes are producing greenhouse gases such as methane and nitrous oxides. The zones can be a bad thing when they expand, so we need to understand why they form and how they influence the marine food webs. So we're interested in the Marine Group A microbes, because they're so abundant in these regions and may produce some of these important green house gases."

"Other scientists are developing computer models of microbial communities to better understand their role at the base of the food chain," he adds. "Our experiments can provide the data that is needed to set realistic parameters for these simulations."

"All this is very exploratory," he says. "We can do this kind of science because of the UA's outstanding capabilities for high-throughput genomics, proteomics and bioinformatics. If you want to study complex biological interactions on the level of ecosystems, you need that kind of infrastructure. It allows you to open new windows into biology."

Provided by University of Arizona