Julie W. Ambler

Department of Biology
Millersville University
Millersville, PA 17551

Nancy M. Butler

Department of Biology
Kutztown University
Kutztown, PA 19530

We all know about the larger animals in the ocean—fish, marine mammals, octopus, squid, and jellyfish. Like terrestrial animals, these ocean dwellers have to get their food from plants or the smaller animals that eat plants. What are all these plants and smaller animals? And how do they fit into the food chains and food webs that link the plants, the animals (herbivores) that eat them, and the animals (predators) that eat other animals (prey)?

What types of organisms are found in the ocean?

Before we learn about the food chains and food webs of the oceans, let's learn a little bit about the organisms found in them. One way that organisms in the ocean are classified is based on where they live and how they move around. Benthos includes organisms that live on or near the bottom of the ocean and includes seaweeds, certain fish, starfish, sea urchins, sea worms, and corals. Nekton includes animals that freely swim and can migrate for many hundreds of miles in the ocean, such as fish, marine mammals, and squid. Plankton includes organisms that move around in the ocean by tides and ocean currents, such as bacteria, single celled algae, jellyfish, and copepods.

There are many different types of plankton. One way we distinguish between the different types is based on how they get their food. Phytoplankton are single-celled algae that produce their own food by photosynthesis. They occur over a wide range of sizes, from photosynthetic bacteria (cyanobacteria) to large diatom chains and dinoflagellates. These larger phytoplankton are visible as small dots to the naked eye. Zooplankton are heterotrophic animals that feed on phytoplankton and other types of plankton. They range in size from protozoans like *Paramecium*, seen under the microscope in introductory biology classes, to the large Portuguese Man-of-War seen on the beach.

Another way plankton are grouped is based on their size (Figure 1). The smallest plankton are viruses, which were discovered in the 1980s [1]. Viruses live by stealth: they enter host cells and take over the host cell to make more viruses. Most known marine viruses live in bacteria, although some marine viruses attack phyto- and zooplankton. The next smallest size of plankton is dominated by bacteria. In the 1970s, marine biologists discovered how abundant very small bacteria were in the ocean because of new microscopic techniques [2]. Bacteria obtain their food by absorbing organic molecules or by using the Sun's energy to photosynthesize. The next larger plankton are mostly single-celled protozoans and photosynthetic algae, but also include some larval stages of multicellular organisms. Larger multicellular plankton include almost every known animal group either as larval stages of benthic adults (barnacle larvae, for example) or as animals that live their whole life in the plankton, such as copepods. Multicellular plankton can be microscopic, such as copepods and larvae which are no larger than a grain of rice, or they can be much larger and easily observed, such as jellyfish.

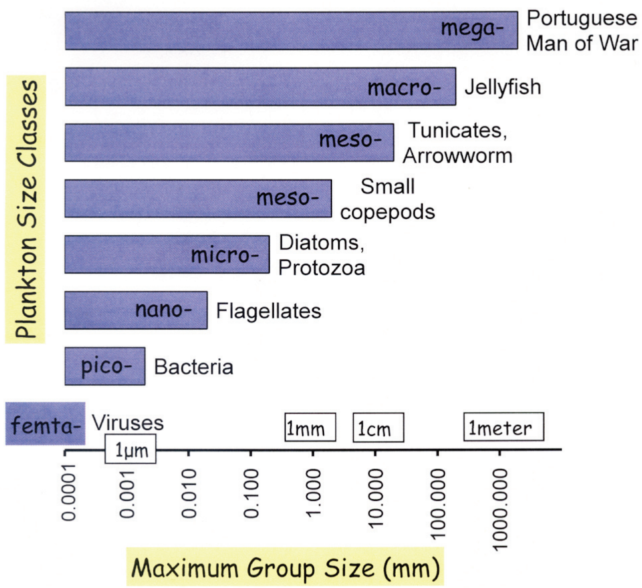

Figure 1. Plankton size classes displayed on a logarithmic scale from .0001 mm to 1000 mm (1 m). Bars show the maximum size for each plankton group. Note that the mesoplankton are represented with two size bars, reflecting a size range that spans two orders of magnitude, from 0.2 to 20 mm. Adapted from Sieburth et al. (1978) [3].

Where do the plankton live in the sea?

Plankton are not found in every part of the ocean. Phytoplankton, like trees and grass, require sunlight for photosynthesis; thus you would expect to find them where there is a lot of light in the water. As you might imagine, there is a lot of light in the surface waters of the ocean. In deeper coastal waters, however, sunlight does not reach the bottom, because it is absorbed and scattered by water molecules and particles. The surface layer of water, where there is enough light for photosynthesis, is called the photic zone. This is where the phytoplankton must live to get enough light to photosynthesize their food. Worldwide, photosynthesis by phytoplankton is as much as photosynthesis by land plants [4]!

Because zooplankton feed on phytoplankton, you would expect to find them where the phytoplankton are most abundant; and that is true. The zooplankton must spend a lot of their time in the photic zone so they can eat the phytoplankton, however, when they are in these brightly lit waters, they run the risk of being seen by their predators. So how do they escape predation?

How do zooplankton escape predators?

The transparent sunlit waters found at the surface of the ocean offer no place for prey to hide from their predators. So, instead of hiding behind a tree, or under a rock, they have other mechanisms for avoiding detection by their predators. The most obvious adaptation is that plankton are small and transparent, which greatly reduces their visibility in surface waters [5]. In addition, because they have high rates of reproduction, individuals are quickly replaced. Populations of single-celled organisms grow rapidly by individuals dividing in two. Populations of multicellular organisms may also grow rapidly by asexual reproduction (for example, cladocerans and tunicates). Although individuals may be eaten, these populations may "escape" predation by producing more new individuals than the number that are eaten.

Slower growing, sexually reproducing zooplankton can avoid predation by vertical migration between the sunlit surface and deeper, darker waters. Many copepod species perform diel vertical migration, which means that they eat phytoplankton in surface waters during the night, but sink or swim to deeper water during the day to avoid visual predators such as fish. However, reverse vertical migration was observed in Puget Sound: copepods migrated to the surface during the day and to deeper waters at night. This reversal appeared to be caused by invertebrate predators such as chaetognaths doing "normal" vertical migration, migrating to the surface at night and to deeper waters at night [6]. Diel vertical migration appears to be a flexible behavior that is influenced by the presence or absence of fish and invertebrate predators, but may also be influenced by feeding habits and reproductive habits. A food web includes all of these interactions—zooplankton eating phytoplankton, invertebrate predators eating zooplankton, and fish predators eating zooplankton.

Food chains and food webs

Scientists once believed that ocean ecosystems were characterized by very simple food chains. In a food chain, the phytoplankton are eaten by copepods, which are eaten by sardines and anchovies, which are eaten by striped bass and blue fish, which are eaten by tuna and sharks. This linear arrangement of predation was the classical picture of ocean food chains until the 1970s. Then, marine biologists began to discover that most photosynthesis and respiration in the ocean was by microorganisms less than 20 micrometers (μm) in size, rather than larger phytoplankton and animals [7]. These microorganisms compose the microbial loop, which includes bacteria, viruses, protozoa, and small phytoplankton [8]. The simple food chain which progresses from one trophic level to another has been replaced by a more complex food web, which includes the microbial loop (Figure 2).

Bacteria are usually thought of as decomposers, but in marine food webs they are a key player in the microbial loop where their food is a soup of dissolved organic matter (DOM). This DOM soup comes from several sources [8]. Phytoplankton release DOM to the ocean around them. Copepods produce DOM when they eat phytoplankton cells; sometimes they break open the phytoplankton and DOM spills out into the ocean from this "sloppy" feeding. Finally, viruses may cause DOM to spill out of their hosts. Much of the DOM is too large for bacteria to eat, so bacteria release enzymes into the ocean to break apart (digest) the larger DOM into smaller pieces.

So far in the microbial loop, DOM has moved from phytoplankton, zooplankton, and viruses to bacteria (Figure 2). What eats the bacteria? Bacteria are eaten by protozoa: flagellates such as *Euglena* and ciliates such as *Paramecium.* Bacteria are also eaten by larger zooplankton called tunicates, which are primitive chordates [9]. Some tunicates filter feed by pumping water into their bodies, collecting particles that become attached to a sticky "style" which is digested [9]. Copepods, however, cannot eat bacteria because these cells are too small; instead, copepods eat ciliates and flagellates, which eat bacteria [10]. In this way, the microbial loop connects back to the food chain: copepods eat protozoa which eat bacteria which eat DOM from phytoplankton. Instead of transferring organic matter from phytoplankton to copepods directly, there is a loop in this food web.

Marine biologists also have new ideas about predators. Besides fish predators, there are invertebrate predators: jellyfish, ctenophores (comb jellies), and chaetognaths (arrow worms) [11]. In addition to copepods, these predators eat a wide variety of prey: larvae of benthic invertebrates, fish larvae, protozoan flagellates and ciliates, and even other planktonic predators [11]! Examples of some of these organisms can be seen in Figure 2 and Figure 3.

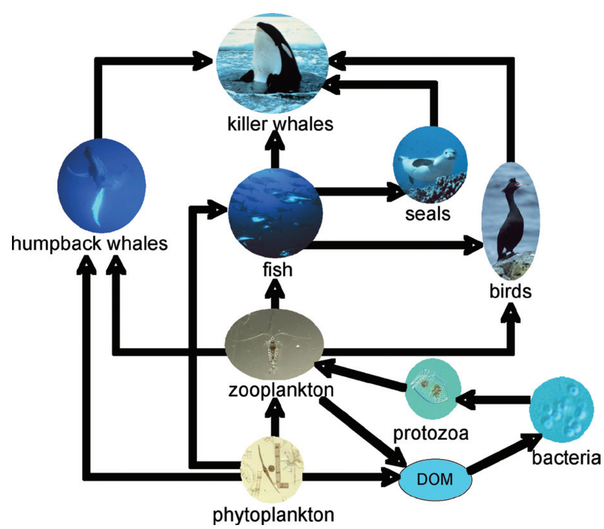

Figure 2. Marine food web with the classical food chain of phytoplankton, zooplankton, fish, and whales. Note that humpback whales are baleen whales, which strain plankton through their baleen. Seals and birds breathe air as do whales. The microbial loop [dissolved organic matter (DOM), bacteria, and protozoa] is the most recently discovered part of the marine food web. (Photographs are courtesy of the National Oceanic and Atmospheric Administration/Department of Commerce and the Bigelow Laboratory for Ocean Sciences.)

How do planktonic food webs affect you?

Marine food webs play a significant role in global warming caused by humans burning fossil fuels which increases the carbon dioxide in the atmosphere. Marine food webs decrease atmospheric carbon dioxide through a "biological pump," which moves carbon from surface waters to the bottom of the ocean. The pump starts with phytoplankton taking up carbon dioxide during photosynthesis [4]. Phytoplankton growth causes more carbon dioxide to enter the ocean from the atmosphere. The carbon in phytoplankton enters the marine food web (Figure 2) and is removed from surface waters to the deep ocean, where it will stay many years before it is returned to the atmosphere.

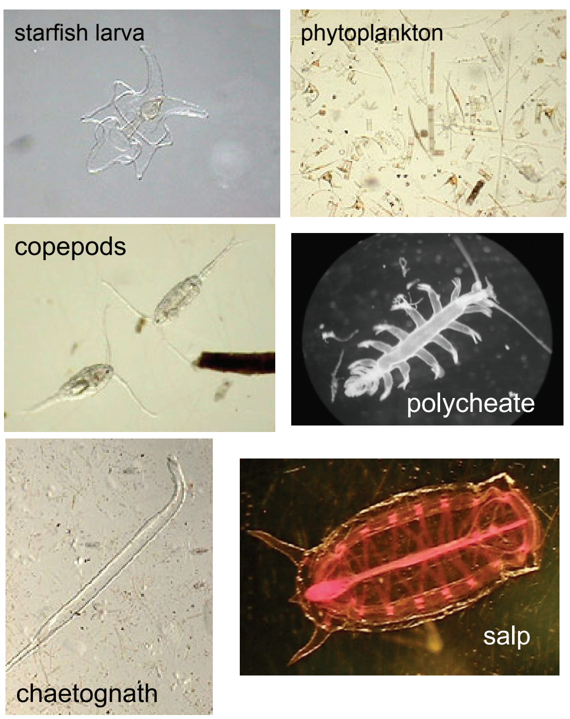

Figure 3. Examples of some of the planktonic organisms mentioned in this article. The salp has been colored with a purple stain to make it more visible. (Photograph of salp and polycheate by Dr. J.W. Ambler; other photographs courtesy of the Bigelow Laboratory for Ocean Sciences.)

How does carbon dioxide get removed from surface waters?

When zooplankton migrate to greater depths, they may be eaten and not return to the surface. In addition, carbon moves downward with the sinking of fecal pellets and dead calcium carbonate shells of small marine animals. The ocean removes approximately half of all the carbon dioxide that humans put into the atmosphere from fossil fuels and clearing forests [12]. Without the biological pump, there would be more carbon dioxide from humans in the atmosphere and probably faster global warming.

How do marine biologists study oceanic food webs?

Marine biologists have been studying food webs for a long time. Many study the interactions between predator and prey, or between an herbivore and phytoplankton. Putting the whole picture together is a daunting task. Marine biologists are like detectives and use as many types of evidence as possible: feeding experiments, long term-sampling programs, satellites, and computer models. They anchor buoys in coastal waters to collect temperature and current data over long periods of time. Satellites continuously record sea surface temperature and ocean color, which is used to measure phytoplankton abundance [13]. These continuous records of the environment show effects of storms and seasonal patterns. Biologists collect plankton samples to see how they are affected by the physical environment and food web interactions. Our project off the coast of Wallops Island, Virginia, combines all these approaches to understand food web interactions in the coastal ocean.

Acknowledgments

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Additional Reading

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C.D. Todd, M.S. Laverack, and G.A. Boxshall, *Coastal Marine Zooplankton, a Practical Manual for Students,* 2nd ed., Cambridge: Cambridge University Press, 2003.

Web Sites

http://faculty.washington.edu/cemills/

Dr. Claudia E. Mills is a research scientist at the University of Washington who works on the gelatinous zooplankton, especially jellyfishes and ctenophores. Her Web page contains a wealth of information on a wide variety of jellies and includes links to Web pages of other scientists working on jellies.

http://www.uwm.edu/People/jrs

Dr. Rudi Strickler is a faculty member at the University of Wisconsin–Milwaukee who specializes in filming the behavior of zooplankton. His Web page contains information on the biology and behavior of copepods and cladocerans and includes a large number of fascinating, and often amusing, video clips.

http://jaffeweb.ucsd.edu/pages/celeste/copepods.html

The Virtual Copepod Page is the result of a collaboration between three plankton biologists: Celeste Fowler at Scripps Institute of Oceanography, Dr. Jeannette Yen at Georgia Institute of Technology, and Dr. Jules Jaffe at the Scripps Institution of Oceanography. Their Web page presents a variety of still images, animations, and movies depicting the behavior of copepods, and also provides links to other copepod Web pages.

http://www.bigelow.org/education.html

The Bigelow Laboratory for Ocean Sciences offers a wide variety of activities, information, and resources for students and teachers wishing to learn more about food webs and processes in the oceans.

http://www.biosci.ohiou.edu/faculty/currie/ocean/

Dr. Warren J.S. Currie is a faculty member at Ohio University. His Web page, "The Plankton Net," offers a diversity of resources pertaining to plankton ecology, marine biology, and biological oceanography, including instructions on how to make your own plankton net!

References

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Julie W. Ambler is a professor in the Department of Biology at Millersville University in Millersville, PA, where she teaches ecology and directs undergraduate research. She also teaches biological oceanography at the Marine Science Consortium at Wallops Island, VA. Dr. Ambler received her Ph.D. from the Department of Oceanography at Texas A&M University, where she studied how different types of plankton affected copepod egg production in Galveston Bay. She has also studied deep sea animals off the Oregon coast; vertical migration of copepods from the Pacific Ocean; copepod swarms in mangrove prop roots in Belize, Central America; and models of planktonic food webs for coastal waters off the southeastern U.S. Currently, Dr. Ambler is working with Dr. Butler to study zooplankton from coastal waters off Chincoteague, VA, in a collaborative project with the NASA Goddard Space Flight Center.

Nancy M. Butler is a professor in the Department of Biology at Kutztown University in Kutztown, PA, where she teaches environmental studies, limnology, and zoology, and directs undergraduate research. She also teaches Ecology of Marine Plankton at the Marine Science Consortium at Wallops Island, VA. Dr. Butler received her Ph.D. from the Department of Zoology at the University of British Columbia, where she studied the feeding behavior and ecology of copepods. She has studied plankton communities in ecosystems as diverse as high alpine lakes, the Great Lakes, and coral reefs. Current research projects include studies of the swarming behavior

of plankton, with emphasis on coral reef mysid populations. In addition, she is working with Dr. Ambler on a collaborative project with the NASA Goddard Space Flight Center studying zooplankton communities in the coastal waters off Chincoteague, VA.

Lab Exercises and Activities for Oceanography

References and Links

1. NASA Phytoplankton Web links

   http://www.bigelow.org/foodweb/microbe5.html

   http://phytoplankton.gsfc.nasa.gov/

2. Build a Plankton Net

   http://www.bigelow.org/foodweb/satellite2.html

3. NASA Chain or Web? Web links

   http://www.bigelow.org/foodweb/chain0.html

4. NASA Algal Blooms Web links

   http://www.bigelow.org/foodweb/bloom0.html

5. Visit to an Ocean Planet: Building a Plankton Net, Plankton Identification

   http://topex-www.jpl.nasa.gov/education/activities/ts3meac3.pdf

6. SeaWiFS Activities from the Teacher's Guide

   http://oceancolor.gsfc.nasa.gov/SeaWiFS/TEACHERS/

7. NOAA's Undersea Research Program (NURP)

   http://www.nurp.noaa.gov/Spotlight/ContObserv.htm

8. EPA Mid-Atlantic Integrated Assessment (MAIA) New Indicators of Coastal Ecosystem Condition

   http://www.epa.gov/maia/html/indicators.html

9. Bigelow Laboratory for Ocean Sciences

http://www.bigelow.org/education.html

10. Flow-cam Instrument for continuously monitoring and imaging phytoplankton

    http://www.bigelow.org/flowcam/flo_e2.html

11. Foundations of Phytoplankton

    http://phytoplankton.gsfc.nasa.gov/

Glossary

Asexual reproduction—reproduction of new individuals occurs by a single cell splitting in two or by a multicellular organism budding new individuals. Any reproduction that does not involve the joining of egg and sperm.

Buoys—floating objects that are anchored to the bottom, usually used to mark entrances to harbors or positions of crab pots. Scientists use buoys to collect data.

Chordates—animals that have, at some stage of development, a primitive backbone, dorsal nerve chord, gill slits, and tail. Humans and all other vertebrates are chordates.

Copepods—small crustaceans that resemble shrimp, sometimes called the "insects of the sea" because they are so numerous.

Diel—24 hour period that includes day and night.

Dissolved organic matter (DOM)—complex organic molecules such as carbohydrates, proteins and fats.

Fecal pellets—feces of zooplankton which are produced in compact oblong cases.

Heterotrophic—eating other organisms to gain food.

Organic molecules—molecules that contain carbon and hydrogen, and often other atoms such as oxygen, nitrogen, phosphorus, and sulfur.

Photosynthetic —using the Sun's energy to produce food.

Sexual reproduction—formation of a new individual by the joining of egg and sperm.

Trophic level—levels of a food chain such that each higher trophic level is further away from the primary producers, which are in the first trophic level.