Brainstorming on ocean literacy

Component idea	2 Interdependent relationships in ecosystems	3 Cycles of matter and energy transfer in ecosystems	4 Ecosystem dynamics, functioning, and resilience	5 Social interactions and group behavior
1 Aquatic microbes—abundance and diversity				



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Component idea	Grade band endpoints	Example	Class activities	Crosscutting concepts
1 Aquatic microbes—abundance and diversity	**By the end of grade 2**. Oceans and lakes are teeming with life almost imperceptible to the naked eye. Microbes have different shapes and colors, and they thrive in ice, water, air, and soil.	Coccolithophores are plant-like microbes, smaller than a grain of dust and widespread in the sunlit ocean. They are round and armored with minute plates of different shapes and patterns[23,24].	Introducing marine microbes as phytoplankton and zooplankton via stories and picture books[25–27].	• Patterns • Scale, proportion, and quantity • Structure and function
	By the end of grade 5. Aquatic microbes have diverse lifestyles. They live as plankton, in biofilms, or in symbiosis with animals and plants.	Zooplankton is a group of single-celled organisms or minute invertebrates that drift with the currents and consume phytoplankton as prey[28].	Creating a plankton net[29], collecting samples from every water body[30], and observing with a microscope[12,31].	• Patterns • Scale, proportion, and quantity
	By the end of grade 8. Aquatic microbes are ancient and diverse, comprising archaea, bacteria, fungi, eukaryotes, and viruses.	Coccolithophores originated about 250 million years ago[24]. Their miniature chalky plates remain in the fossil record, forming massive chalk formations[32].	Exploring geological chalk formations in field trips[17]. Ask which (micro)organisms produce chalky shells? How may this trait benefit marine microbes [23]?	• Cause and effect • Scale, proportion, and quantity • Energy and matter
	By the end of grade 12. Most of the marine biomass is microbial. Microbes and their metabolic traits play key roles in the evolution of life on Earth.	Cyanobacteria originated ~3.5 billion years ago. Their photosynthesis oxygenated the atmosphere, allowing the evolution of multicellular life[24,33].	Constructing the timeline of life on Earth as a 24 h clock, emphasizing the emergence of microbes and their evolutionary roles[24,34].	• Cause and effect • Scale, proportion, and quantity • Energy and matter • Stability and change

				change
2 Interdependent relationships in ecosystems	**By the end of grade 2**. Aquatic microbes depend on the environment to get food, light, and a favorable temperature. Some microbes make their food, like plants, while some eat other microbes. Many can do both! Microbes sense and respond to their environment – they have cell parts used for swimming, eating, and protection.	Many marine bacteria are motile—they have long extensions called flagella, which propel and help them to swim and find small particles to eat[35]. Bacteria also swim to avoid danger. For instance, to stay away from predatory microbes.	Designing microbes from clay or fabric. For example, a bacterium can be an oval cell with a flagellum attached. Designing a playroom inspired by the ocean (for instance, a coral reef) and engaging in play with the models. Get creative, there are many inspirational examples online!	• Cause and effect • Scale, proportion, and quantity • Structure and function
	By the end of grade 5. Microbes serve as the base of marine food webs. Microbes have diverse nutritional strategies, as consumers, producers, and mixotrophs. Fungi, bacteria, and viruses recycle dead matter back into the water for other microbes to use.	• Coccolithophores are primary producers-they perform up to 10% of the global photosynthesis[32]. • The bacterium SAR11, the most abundant organism on Earth, is a consumer that requires very few elements to grow[36,37].	Incubating phytoplankton culture (as coccolithophores) or samples from the environment in various light intensities. Monitoring cell density over 1–2 weeks by eye or microscope[18]. Asking what could be the reason for culture clearing under darkened conditions?	• Scale, proportion, and quantity • Structure and function • Systems and system models
	By the end of grade 8. Aquatic microbes depend on biotic interactions and abiotic factors such as nutrient availability, temperature, and light. Microbes may compete for limited resources. Microbes develop defense strategies against	• Dinoflagellates are microbes that can produce light (known as bioluminescence) as a "burglar-alarm" to avoid predation by zooplankton[38]. • A microbial parasite led to a recent pandemic and mass mortality of sea	• Investigating microbial bioluminescence in culture-based experiments[20]. • Creating a concept map to illustrate relationships between abiotic factors, marine microbes, and larger organisms,	• Cause and effect • Systems and system models

Table 1 (continued) | Incorporation of marine microbiology into the NRC Framework for K-12 Science Education

Component idea	Grade band endpoints	Example	Class activities	Crosscutting concepts
	predators and pathogens. Prey-predator dynamics control population size and composition.	urchins, endangering coral reefs that depend on the urchins' ecological services[39].	and anthropogenic perturbations in oceanic ecosystems.	• Stability and change
	By the end of grade 12. The complex interactions between bottom-up (nutrient, light) and top-down forces (predators, pathogenic bacteria, parasites, and viruses) govern microbial population dynamics.	• Marine bacteria can exploit organic matter in the water to enhance their growth by using chemotaxis or diffusion[35]. • When the environmental conditions support their proliferation, some phytoplankton (as coccolithophores) form seasonal blooms visible from space[40].	Monitoring phytoplankton growth in response to various nutrient levels (as phosphate and nitrate)[18]. Comparing the approximate (calculated or measured) nutrient level in the experiment with in situ concentrations by using available oceanographic databases or AI tools.	• Cause and effect • Scale, proportion and quantity • Energy and matter • Structure and function

3 Cycles of matter and energy transfer in ecosystems	**By the end of grade 2**. Aquatic microbes obtain the materials they need to grow and survive from the environment. They are so small and live in water, hence obtaining what they need is a challenging task!	• Like plants, phytoplankton require light and nutrients to grow. • A microbe swimming in water is analogous to a man swimming in honey. Many cells have long extensions that beat and bring food closer to the cell[41].	• Observing microbes in action in excursions to coasts, lakes, and hypersaline environments[17]. • Moving like a microbe- practicing yoga, dancing, or walking as if we were surrounded by honey.	• Scale, proportion, and quantity • Energy and matter
	By the end of grade 5. Microbes affect water composition through biological processes: they obtain gases, water, and minerals from the water and release materials (gas, liquid, or solid) back into the water. They often help their environment, but some microbes can be harmful.	• Phytoplankton fix CO_2 and release oxygen during photosynthesis, and they do so in the same capacity as all land plants[42]. • Some phytoplankton produce toxic compounds that accumulate in the food web[43].	Breathing exercise- take a breath, thank the trees. Taking another breath- thank the phytoplankton. Discussing how our daily actions may be linked to marine microbes? Reflecting on possible positive and negative influences of our activity on the plankton, and vice versa.	• Energy and matter • Cause and effect
	By the end of grade 8. Microbes are powerful thanks to their vast numbers, huge taxonomic and functional diversity, and different ecological niches. They act as tiny engines that drive biogeochemical cycles of carbon, nitrogen, and phosphorus in the ocean. Microbes can transform elements, making them bioavailable for other organisms to use.	Viruses are the most abundant biological entity in the ocean. When they infect and kill microbes (such as coccolithophores), the cells degrade, and their content is released as dissolved matter, providing food for bacteria rather than for predators up the food chain (the "viral shunt hypothesis"[44]).	Sampling mud and water from every water body (salt marsh, sea, and lake) to assemble Winogradsky columns, monitoring by eye, and discussing the possible causes for the colors and smell that emerge over time[7]. Quantifying bacteria by staining and microscopy. Describing the potential microbial interactions that take place in the experiment.	• Scale, proportion, and quantity • Energy and matter • Systems and system models
	By the end of grade 12. Microbes sequester, transform, and shuttle carbon into the ocean interior. Their joint biological activity drives a "carbon pump" from the surface to the seabed, where it eventually transforms into oil and natural gas.	When marine organisms die, their remnants sink to the ocean interior, creating a shower of organic matter that looks like snowflakes. As they descend, these so-called "marine snow" particles are hubs for microbes to eat and interact[45].	Drawing a possible journey of a carbon molecule. For example, a CO_2 molecule is emitted from an airplane, then absorbed by seawater and dissolved, fixed by phytoplankton, and moved to a predatory microbe, which gets eaten by a larger zooplankter…	• Cause and effect • Energy and matter

4 Ecosystem dynamics, functioning, and resilience	**By the end of grade 2**. The ocean and humans are connected. The ocean provides the air we breathe, food, and a habitable climate. Our activities change the ocean, slowly or rapidly, with various impacts on all lifeforms, from microorganisms to mammals.	Plastic bags and other waste are shredded by the sun, water, and wind into particles; some can be seen in the water or sand, but most of them are too small to be seen by eye. Plankton can mistake plastic for food, which endangers them and the animals they support[46].	Beach-cleaning, including the collection of plastic waste to create artwork inspired by marine microbes (for example, a mural from bottle caps). The projects can be presented in an exhibition to raise awareness of plastic pollution, sustainability, and ocean microbes.	• Cause and effect • Stability and change
	By the end of grade 5. The rise of anthropogenic greenhouse gases in the atmosphere leads to ocean warming, which melts sea ice, alters ocean currents, and affects nutrient availability. These transformations risk some microbes, while others survive or may thrive in habitats with better conditions, with a cascading effect on the food web.	• Global warming changes algal bloom dynamics, potentially increasing the frequency of harmful blooms by toxic species in locations with high ecological importance and economically important fisheries[43,47]. • When sea ice melts, frozen bacteria and viruses are released into the water and could potentially infect wildlife and cause disease. They can also infect microorganisms and thus impact the flow and fate of major nutrients[48].	Monitoring plankton growth in response to increasing water temperature[18]. The tested temperatures can relate to the IPCC forecasts according to different greenhouse gas emission scenarios. Asking what cellular mechanisms and structures may be modulated by temperature?	• Cause and effect • Systems and system models • Stability and change
	By the end of grade 8. Human activity and climate change lead to shifts in seawater temperature and chemistry, which modulate microbes' biodiversity, alter their	• Calcification by coccolithophores and foraminifera is threatened by ocean warming and acidification, leading to populations decrease, with implications	Identifying main microbial groups in live samples by morphological characteristics (use plankton guides and online tools)[12,50]. Test the effect of different plastic beads on	• Patterns • Cause and effect

Table 1 (continued) | Incorporation of marine microbiology into the NRC Framework for K-12 Science Education

Component idea	Grade band endpoints	Example	Class activities	Crosscutting concepts
	community composition, and endanger their ecosystem functions.	for the marine carbon cycle[15]. • Pollution of coastal waters enhances algal growth (known as eutrophication), including toxic species, with negative effects on local marine life[12,49].	microbial diversity and abundance over time. Ask how different functional groups may be affected by seawater warming, acidification, or pollution?	• Stability and change
	By the end of grade 12. Anthropogenic CO_2 emissions are being absorbed by the ocean, dissolved, and removed by microbes into the depths. Microbes modulate the climate not only by regulating atmospheric CO_2 but also by generating gases that are emitted into the atmosphere.	Coccolithophores and dinoflagellates produce a gas called dimethylsulfide, which is emitted to the atmosphere and promotes cloud formation. Increasing cloud cover may enhance Earth's albedo and help to cool the climate[51].	Connecting scales- draw a scale from microns to thousands of kilometers. Add biological complexity to the scale (such as cell, population, ecosystem, etc.). Add examples from the ocean (e.g., from a coccolithophore cell to the global climate).	• Cause and effect • Scale, proportion, and quantity • Stability and change

5 Social interactions and group behavior	**By the end of grade 2**. Microbes are social- they can help each other to obtain food and cope with environmental change. They can fight each other or compete for nutrients and space. Many microbes live inside organisms, helping them to eat and grow.	Corals and sea anemones are sessile animals that host tiny photosynthetic microbes inside their tissue. The animals get food from their microbes, and the microbes get protection and nutrients from their animal host.	Visiting aquariums. Discussing friendship (symbiosis) between microbes and the different animals observed in the tour (as corals)[17]. Asking what could interrupt their relationship, and why?	• Scale, proportion, and quantity • Structure and function • Stability and change
	By the end of grade 5. Microbial interactions can be interspecific or intraspecific. Microbes can grow as individual cells, in chains, colonies, and biofilms. Some microbes can form vast blooms.	Microbes such as diatoms form chains or break into single cells. Chain length is a plastic trait and can serve as a strategy to escape zooplankton predation[52].	Examining plankton from field samples or cultures with a microscope[31]. Drawing the cell/chain structures and discussing the pros and cons of each state. Drawing the various cell parts and discussing possible functions.	• Patterns • Scale, proportion, and quantity • Structure and function
	By the end of grade 8. Microbes modulate carbon flow in the food web via symbiosis, predation, and pathogenicity. Microbial interactions ultimately impact vast scales of space and time. Therefore, the effects of ocean acidification and warming on microbial cells have cascading effects on entire ecosystems.	About half of the photosynthetically fixed carbon goes up the food chain to zooplankton and fish, while the other half is recycled in a "microbial loop"- which starts with bacteria consuming dissolved carbon that exudes from phytoplankton cells, continues to predators of bacteria (protists), and then to larger zooplankton[53].	Exploring algal blooms from space using the NASA website. Discussing the possible factors leading to bloom development and demise. Asking how warming and ocean acidification may modulate bloom dynamics and carbon fluxes?	• Scale, proportion, and quantity • Energy and matter
	By the end of grade 12. Anthropogenic activity and global warming interfere with microbial interactions and introduce invasive species into new habitats, including pathogens. These may harm sensitive species while benefiting other species. Consequently, the ecological balance, regional productivity, and carbon flow and export into the sediment for long-term storage are all impacted.	• Warming modifies cellular traits such as membrane stability, which could expose microbes to pathogenic attack by viruses[54]. • Coccolithophore blooms are changing in duration and location, and are developing in cooler habitats in higher latitudes[54].	Visiting a local academic institution that conducts marine microbiome research. Touring in labs and interviewing marine microbiologists, inquiring about lab life, main research questions addressed and how, the motivation behind their study, and possible links to climate change, etc.	• Cause and effect • Energy and matter • Stability and change

Grade band progression is described as part of the Core Idea Life Science 2: Ecosystems: Interactions, Energy, and Dynamics[5], with an addition of component idea no. 1 (Aquatic microbes—abundance and diversity). Examples from the marine microbiome are presented, as well as recommended class activities. The relevant scientific crosscutting concepts that are being addressed in each grade band are specified[13].

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Comment

https://doi.org/10.1038/s44168-025-00325-3

Bringing marine microbiome research into the classroom is an essential step toward a climate literate society

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