Scientific Concepts for Understanding the Health of the Chesapeake Bay and Its People

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The same science speaks to the body and the Bay
It explains how in each, the components come together in an integrated way
Oxygen, nutrients, and energy flows
In the Chesapeake and down to our fingers and toes

Abstract

This chapter provides an introduction to the basic science needed for the reader to understand the ensuing chapters that explore the relationship between the health of the Chesapeake Bay, its food system, and the wellbeing of its people. For many readers, high school or college science courses may sit dim in their memories. This chapter will refresh some of those old facts and concepts, as well as introduce some important new ones. It focuses on the most important aspects of physics, chemistry, biology, and ecology needed to understand the subsequent material. Whenever possible the chapters apply the same scientific principles to explain phenomena that are common to human health and that of the Chesapeake Bay Ecosystem.

Keywords

Estuarine ecosystem · Human health · Circulation · Nutrition · Food system

Systems of Life

Life scientists typically organize the living world with a system of hierarchical classification. The classification starts out with atoms that are organized in molecules. The molecules of life form the bits of living cells. Each cell may be a free living individual or organized with other cells into a more complex multicellular organism. In more advanced organisms (plants, animals, and fungi), the cells are further organized into tissues and organs with specialized functions. The organs work together in organ systems. Whether simple or complex, each organism belongs to its own species. Members of the same species in an area constitute a population. All the populations that interact in an area comprise the living community. The community is also the living portion of an ecosystem. The ecosystem includes non-living attributes too, such as minerals, gases, water, and temperature.

At first glance a body of water and the human body seem to share little in common. Yet each is like the other in many important ways. Both are living systems that share similar functions. Each requires inputs of energy and materials that are processed or metabolized, yielding various outputs. The Chesapeake Bay system is mostly water and so are people. The Bay uses energy and basic nutrients to build elaborate life forms. People use their food system to do much the same to build and maintain their complex bodies.

The Chesapeake Bay and its surrounding land is an ecosystem, comprised of many different species and the non-living aspects of the environments. Humans are but one of many populations of species that constitute the community of life in the Chesapeake Bay ecosystem. Traditional science classifies human beings as distinct individual organisms, organized in populations with other members of their same species (Homo sapiens). Yet, a closer look reveals that a human is actually more than just one individual organism. Each human harbors trillions of bacteria, particularly in the intestines. These microbes constitute the microbiome. The tiny bacterial cells of the microbiome outnumber human cells by ten to one and constitute 1–3% of the body’s mass (NIH 2013). Indeed,
human health depends upon a well-functioning microbiome in the gut. So, in a sense, an individual human is a bit of an ecosystem unto itself.

**The Chesapeake Bay is an Estuary** Estuaries are semi-enclosed bodies of water found where rivers enter the ocean (Cuker and Bugyi 2016). The Chesapeake Bay is neither a freshwater river nor a salty ocean, but a mix of both. The freshwater entering the bay drains from a watershed that includes six different states. That watershed is a patchwork of forest, agricultural lands, suburban and urban communities, industrial sites, towering mountains and marshy plains. The substances carried by water draining from this diverse landscape determine the health of the Bay. In many ways, the watershed and Atlantic Ocean feed the Bay in the same way that people drink and eat to feed themselves.

The Bay and its numerous tributaries are home to a variety of plants and animals that thrive in the special conditions provided by the estuarine environment. Subsequent chapters will explore the details of how our quest for food reshaped the Bay. For now, keep in mind that the Chesapeake Bay is a product of the interaction between land, atmosphere, sea, and life. And understand that the Bay ecosystem is much more than the water that laps its shores.

**A Taste of Water Chemistry** Since the Chesapeake Bay is foremost a body of water and the people that live there are foremost made of water (about 60% by weight), and our food system depends on water, it is important to understand something about the nature of water. To understand the special properties of water so important to the functioning of the Bay and its people, one needs to understand some basic information about the chemistry of water molecules. A molecule of water is comprised of two tiny atoms of hydrogen (H) and one bigger one of oxygen (O). The atoms are held together by sharing electrons that orbit around their respective nuclei. This is called a covalent bond which is very strong. Each of the two hydrogen atoms shares one electron with the oxygen atom, making for a very stable molecule of water. The shape of a water molecule resembles “Mickey Mouse ears,” with an angle of 104.5° between the two “ears” of Hydrogen atoms attached to Mickey’s head of Oxygen (Fig. 1) (Cuker and Bugyi 2016).

The atom of oxygen in a water molecule is much larger than each atom of hydrogen. Oxygen has eight neutrons (neutral charge) and eight protons (positive charge) in its nucleus. Hydrogen, the smallest of all atoms, only has one proton and no neutron in its nucleus. When oxygen and hydrogen are separated from each other, each atom is unstable. The oxygen needs two electrons (negative charge) to achieve a full and therefore stable outer shell of electrons. The hydrogen needs just one electron to achieve stability. For water, one oxygen atom achieves stability by bonding with two hydrogen atoms. But here is the interesting part, since oxygen has eight protons in its nucleus and hydrogen has only one, the shared negatively charged electrons spend most of their time near the oxygen atom. It is said that oxygen is more electropositive than hydrogen, its eight protons being more attractive to electrons. That means that the oxygen end of the water molecule has two negative charges associated with it, while each of the hydrogen atoms has one positive charge. This arrangement of charges causes water to be a polar substance, with a positive end and a negative end (Fig. 1). And this is essential as it is the basis for all of the very special properties of water.

Because water molecules are polar in the liquid and solid states, they interact with each other in a particular way. The negatively charged oxygen ends of one molecule of water will attract the positively charged hydrogen ends of two adjacent water molecules. That attractive force between the positive and negative aspects of adjacent water molecules is called a hydrogen bond. When in the liquid state, each molecule of water forms hydrogen bonds with about 3.4 other water molecules at a time, with four being the maximum (Armstrong 1983). So, if a thimble of water contains billions of water molecules, it also contains up to four times that many hydrogen bonds that join the water molecules together (Fig. 2).

Individually, hydrogen bonds are weak. Recall the covalent bonds holding the hydrogen atoms to the oxygen atom. The energy required to make or break covalent bonds between an H and O is 111 kcal/mole. In contrast, the energy of a hydrogen bond between adjacent water molecules is just one twentieth of the strength of the H-O covalent bond. Yet, water contains so many hydrogen bonds that there is real strength in numbers.
All of those hydrogen bonds give water some very special properties. Water has a very high specific heat, meaning that it takes a lot of energy to add to those hydrogen bonds to cause the water to increase in temperature just one degree Celsius. Indeed, water is the defining substance for specific heat. At standard conditions, the specific heat of water is one calorie per gram. It takes one calorie to heat that water one degree Celsius. In contrast, the specific heat of quartz sand is only 0.19 cal/g (Engineering Tool Box 2016). Thus, the same about of heat that causes 1 g of water to rise in temperature 1 °C would cause the same mass of quartz sand to increase about 5 °C. It is the same story when water loses heat. It takes about five times more heat to be lost from water than it does quartz sand in order for the temperature to drop 1 °C. As such, the Chesapeake Bay takes time to warm-up every spring and cool down every fall. The large mass of water in the Bay also buffers changes in the temperature of the surrounding land. It never gets quite as cold or hot on the shores of the Chesapeake as it does inland 1 km (less than a mile) or so.

In addition to water’s high specific heat, it also takes a lot of energy to change the state of water between solid and liquid, and even more between liquid and gas. The energy exchanged when water goes between ice and the liquid state is 80 cal/g. This is called the heat of fusion. Think of a gram of water at about room temperature, say 22 °C. It would have to give up 22 calories to reach a temperature of 0°C (freezing point of water). But for it to transform to ice it would need to lose another 80 cal.

The structure of ice differs from that of liquid water in two ways. First, the molecules of water in ice form a regular and highly rigid crystal pattern. Second, spaces between the molecules in ice are greater than that for liquid water (Fig. 3). The additional space between water molecules in ice means that it is less dense than liquid water, the same mass takes up more space. This means that solid ice floats on the denser liquid water. As winter settles on the Chesapeake Bay, one often sees ice floating on the surface of its small tributaries.

For 1 g of liquid water to change to gaseous water vapor, 540 calories must be added. This is called the heat of vaporization (540 cal/g). It takes so much energy to evaporate water because it means the complete breaking of nearly four hydrogen bonds for each molecule that becomes a gas. Warming up water requires heat to expand hydrogen bonds, while evaporating water requires much more heat to break those hydrogen bonds. Starting with that 1 g of water at room temperature of 22 °C, 78 calories must be added to bring it to 100 °C (boiling point of water). But it will take an additional 540 calories to evaporate the gram of liquid water into gaseous state. So, it is not just the high specific heat of water that cools adjacent lands during the summer. It is also the huge amount of heat dissipated by the Bay as it evaporates water from its surface. People of the Chesapeake region directly experience the power of evaporative cooling every summer, as they sweat their way through those hot months of the year. But when the air becomes saturated with water on the most humid days, people get less relief. The air can hold no more water so that the perspiration coalesces into drops that fail to evaporate, leaving folks both hot and wet.

Above it was noted that ice is less dense than liquid water and as such it floats at the surface of the wintery Chesapeake. But temperature also affects the density of liquid water and this is key to understanding important patterns of circulation in the Bay, particularly in the warmer months. For fresh water, maximum density occurs at 4 °C. As freshwater cools below 4 °C it begins to expand, becoming less dense. For temperatures above 4 °C, the warmer the water the less dense it is. Just like cold ice in the winter, the warmest and lowest density water floats on top of the cooler and denser water during the summer. This has profound implications for how the Chesapeake Bay functions, and it gets a bit more complicated when we consider the saltiness of the system, to be explained below.

That water is H2O, is only mostly true. In fact, water appears in nature mostly as H2O, but importantly a small portion of that water disassociates into ions (charged molecules or atoms) of H+ and OH−. Pure water is said to be a weak acid, since the small portion of the water that does disassociate produces more H+ ions than it does OH− ions (Fig. 4). A substance like ammonia (NH3) disassociates partially and produces more negatively charged ions so it is called a weak base.

The pH scale is used to measure the acidity of a solution (Fig. 5). When the concentrations of H+ and OH− ions are equal, the solution is neutral and has a pH of seven. Why seven? The term pH is shorthand for the −log of the hydrogen ion activity (think concentration). So, at pH 7, the concentration of H+ is 10−7 moles/liter and the concentration of OH is also 10−7 moles/liter (a mole is the mass of a substance containing the same number of fundamental units as there are atoms in exactly 12 g of carbon 12). Water with a pH less
than seven is acid and greater than seven is basic. The pH scale is deceptive, since it is logarithmic. So, water with a pH of five will have 100 times more H+ ions than water with pH of seven. Each pH unit represents a ten-fold change in H+ concentration (Cuker and Bugyi 2016).

Adding or subtracting H+ or OH− ions will change the pH of water. Yet the waters of the Chesapeake Bay and the human body contain dissolved salts that can absorb some of the excess ions. Such salts are called buffers. In the Chesapeake Bay, calcium carbonate (CaCO3), and to a lesser extent magnesium carbonate (MgCO3) serve as buffers. Human blood is also buffered by CaCO3.

Buffers in the waters of the Bay prevent large swings in pH that would otherwise follow acid rain events (from air pollution). Despite these buffers, the Chesapeake Bay is becoming acidified by the increasing levels of carbon dioxide (CO2) in the atmosphere that diffuses into the water (Fig. 6).

Oceanographers once considered the ocean and estuaries like the Chesapeake Bay to be so well buffered that they paid little attention to measuring pH. However, the extensive burning of fossil fuels since the Industrial Revolution combined with deforestation and animal husbandry has driven up atmospheric CO2 levels by 56% (going from 180 ppm to 415 ppm as of 2019) over the last two centuries. Over recent years, the pH of the ocean has dropped from an average of 8.2 to 8.1, meaning a 30% increase in acidity (NOAA 2020). Acidification is worse in the Chesapeake Bay than the ocean due to lower availability of buffers than seawater and production of acids under seasonal anaerobic conditions (Cai et al. 2017). The primary buffer in the Bay, calcium carbonate, is also critical for building the shells of oysters (Crassostrea virginica) and other animals of the Bay. The acidification of the Bay uses up so much of the carbonate buffer, that it makes it harder for oysters to build their shells (Waldbusser et al. 2011).

The carbonate buffering system that helps regulate the pH of the Chesapeake Bay performs the same function in the blood of the people that reside on its shores. Yet, like in the Bay, the buffering is imperfect. And as with the Bay, its people have also become more acidic over recent years. This is not due to carbon dioxide in the atmosphere, but instead diets heavy in animal-based items and light in plant-based foods. Such acid-causing diets are linked to kidney disease and other medical problems (Lin et al. 2010; Deriemaeker et al. 2010; Sebastian et al. 2002). And as noted in later chapters, the production of acid-forming foods (animal flesh) is directly responsible for a large portion of the carbon dioxide that is acidifying the Bay.

**What's in the Water?** At this point the reader knows the essentials about the chemistry of pure water, and a bit about one type of constituent of water, buffers. The Chesapeake Bay is not pure water and quite far from it. It contains a diversity of non-living and living constituents that interact in

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**Fig. 3** The molecular arrangement of liquid water is shown on the left, and that of ice on the right. Note that there is more space between the molecules of ice than liquid water. This makes the ice less dense than liquid water and is why ice floats on the surface of frozen rivers and bays. https://commons.wikimedia.org/wiki/File:Liquid-water-and-ice.png

**Fig. 4** The disassociation of water into ions. https://en.wikipedia.org/wiki/Self-ionization_of_water#/media/File:Autoprotolyse_eau.svg. By Cdang—Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=7942156
a myriad of ways to yield a vibrant system. The same is true of the water circulating in our bodies.

Water is the universal solvent. That means that most substances dissolve, at least to some degree, in water. Recall that water is polar and as such easily dissolves other polar substances. This includes cations (positively charged ions) such as Ca^{++}, Mg^{++}, Na^+ and K^+; anions (negatively charged ions) such as HCO_3^−, CO_3^{−}, SO_4^{−}, and Cl^− and atmospheric gases (O_2, N_2 and CO_2). The polar quality of these entities easily fit into the matrix of liquid polar water molecules. As will be seen later, excess levels of ionic forms of compounds of nitrogen and phosphorus originating from the agricultural...
system play a large role in the degradation of the Bay (See Chapter “The Journey from Peruvian Guano to Artificial Fertilizer Ends with too Much Nitrogen in the Chesapeake Bay”).

The dynamic nature of the matrix of liquid water allows some solubility for non-polar molecules. Non-polar means that the molecules lack distinct positive and negative ends. Familiar non-polar substances are hydrocarbons like petroleum. They consist of hydrogen and carbon. Their non-polar charge distribution keeps them from dissolving well in water, but to some extent they do. Benzene is a good example. It is found in petroleum and pesticides, like those used on crops grown in the watershed of the Chesapeake Bay (CDC 2016). It is a toxin and carcinogen. At standard conditions of 25 °C in freshwater, it has a solubility of 1.8 g/l. Since there are 1000 g of water in a liter, this means that freshwater could be 0.18% contaminated with benzene. That may not seem like much, but it is 36 times the safe limit for drinking water set by the United States Environmental Protection Agency (ATSDR 2007).

Since benzene and other non-polar molecules are much more soluble in other non-polar substances, it is easy to see why they tend to accumulate in the non-polar fatty or oily tissues of animals in the Bay ecosystem, including people. Indeed, many of the toxic residues from the chemical food-system used to grow crops in the watershed are non-polar substances that accumulate in the bodies of bay animals. Now banned, the pesticide DDT was widely used on crops and for mosquito control from 1945. The accumulation of this infamous toxin in the tissues of birds nearly drove to extinction the eagles, cormorants and osprey of the Bay (Watts et al. 2008, See Chapter “Pesticides Bring the War on Nature to the Chesapeake Bay”).

Being an estuary, the water in the Chesapeake Bay has two main origins. Freshwater drains from the watershed and falls from the sky. Saltwater flows in from the ocean.

Freshwater tributaries to the Bay contain a variety of substances derived from the watershed. As rain or melting snow water moves through and across the landscape, it picks up dissolved and suspended particles. The list of cations and anions given above dominate freshwater lakes and rivers. The masses of all of those and other ions in the water total to what is called salinity. Traditionally salinity was expressed as parts per thousand (ppt). Ocean water is typically about 34–37 ppt, which means that there are 34–37 g of salts dissolved in 1000 g (or l) of water (Garrison 2001). Freshwaters are defined as those having salinity less than 0.5 ppt (Wetzel 2001). Note that in recent years many chemical oceanographers prefer to present the measure as simply salinity, without the units of concentration for technical reasons addressed in the previous chapter.

The freshwater from the land and the saltwater from the ocean mix along the length of the Chesapeake Bay, creating brackish water of intermediate salinity. The salinity of the brackish water in the Bay is very dynamic, constantly changing through time and space, being influenced by rainstorms, droughts, tides, and wind. A gross average of salinity for the Bay is around 14 ppt, close to that of human blood.

The salinity of water is important in several ways. First, the large load of salts makes seawater heavier than freshwater for the same volume, meaning that saltwater is denser than freshwater. One liter of saltwater weighs 1034 g compared to one liter of fresh water at 1000 g. All of those polar salts are filling in the spaces between the water molecules. Recall that temperature also affects the density of water. Freshwater density decreases with increasing temperatures above 4 °C. Water that is both warmer and fresher will float on top of water that is cooler and saltier. As will be seen, differences in water density profoundly affects circulation in the Bay.

Salinity lowers the freezing point of water such that sea ice formation requires a temperature of -2 °C. The added salt also increases the specific heat of water. So saltier waters near the mouth of the Bay won’t cool off or freeze as quickly as fresher headwaters of the Bay’s tributaries.

Salinity is also critical to determining the types of plants and animals that can inhabit a body of water. Water diffuses into and out of the cells of living organisms in a process called osmosis. Water will naturally move toward a saltier solution. Freshwater plants and animals have an internal salinity that is higher than their surroundings. The reverse is true for many forms of life in the ocean; they are internally less salty than the water in which they reside. This means that freshwater fauna and flora must fight the continual intrusion of water diffusing in. It is the opposite for life forms of low internal salinity living in the ocean as they must strive to keep from losing their water to the surrounding sea. However, some marine species survive in different external salinities by changing their internal salinities to match. These are called osmotic conformers, as opposed to the osmotic regulators that spend energy to control the flow of water between themselves and their surroundings.

As noted above, the salinity in the Bay is highly variable. The plants and animals of the Bay must be able to endure regular swings in salinity that may happen over hours. As such some familiar marine species, such as sea urchins, sea cucumbers, and sea stars are absent from the Chesapeake Bay and other estuaries. They are osmotic conformers and can’t tolerate large swings in salinity that characterize the Bay. All resident and visiting forms of life in the Chesapeake Bay share in common their capacity to thrive in waters of variable salinity.

As with the creatures of the Chesapeake, the people on its shores also have challenges with salt. The Standard American Diet (SAD) includes high levels of salts of sodium chloride (NaCl), which is added to most processed foods. Excess sodium raises blood pressure and increases incidence of heart disease (Whelton et al. 2012; He et al. 2014).
The water of the Chesapeake Bay contains the same gases found in the atmosphere above, most notably nitrogen (N₂), oxygen (O₂), and carbon dioxide (CO₂). N₂ accounts for 78% of the atmosphere, O₂ 21% and CO₂ only about 0.04%. Of these, oxygen is the most critical for higher forms of life in the Chesapeake, including the people that live there.

Oxygen is necessary for the process called aerobic respiration, the metabolic sequences used by cells to release energy from sugars and other organic molecules. A portion of this process is the electron transport chain. High energy electrons released from food, skip down this chain and as they do some of their energy is used to produce ATP (Adenosine Triphosphate). ATP is the direct energy source for most of the chemical reactions in cells. To keep the flow of electrons going down the chain there must be something to remove the electron as it finishes its journey. That something is free oxygen. It readily combines with the now low-energy electron along with hydrogen to form water. Without oxygen to take away the electrons, the transport chain stops, meaning there is no more production of ATP. For higher organisms from fish to humans, the absence of oxygen spells death in a matter of minutes (Armstrong 1983).

There are three ways oxygen gets into the Chesapeake Bay. First, oxygen diffuses from the atmosphere into the surface waters. Wind and waves speed the process and also help mix the newly oxygenated surface water to somewhat deeper depths. Second, water flowing into the Bay from its many tributaries and the ocean brings in its own load of oxygen. This transportation by flowing water is called advection (Garrison 2001).

The third source of oxygen to the Bay is photosynthesis. This is a metabolic process done by green plants and algae that contain the pigment chlorophyll. Photosynthesis uses energy from sunlight to split water molecules into atoms of oxygen and hydrogen. Recall that there is much energy in the covalent bonds that hold together the hydrogen and oxygen atoms of water molecules (Fig. 7). The splitting releases high energy electrons to power the production of ATP. The energy stored in ATP is then used to convert carbon dioxide into sugars, fats, and proteins, the building blocks of life. The oxygen produced by the splitting of water is a waste product, and it is released by the cells into the surrounding water. On a clear, still day along the shores of the Chesapeake, one can look down into a bed of submerged sea grass and see oxygen bubbles floating to the surface.

That oxygen is a waste product might seem strange to most readers. After all, oxygen is critical to the process of aerobic respiration that keeps all higher organisms alive. However, what makes free oxygen so good at picking up those low energy electrons at the end of the electron transport chain in aerobic respiration, also makes it good at disrupting important molecules in the cell by stealing their electrons. If not quickly paired with a second oxygen atom to make O₂, the uncoupled oxygen atom is called a free-radical, ready to steal electrons away from other molecules. This is the process of oxidation and it causes havoc for the fats, proteins, and nucleic acids that are the structural and functional basis of cellular life. So, this benefits plant and algae cells to quickly expel excess oxygen. In addition, plant cells protect themselves from free-radicals with a class of compounds called anti-oxidants. Not surprisingly, it is plant foods that provide humans with dietary antioxidants. And it is the lack of fresh fruits and vegetables in the SAD (Standard American Diet) that leads to diseases associated with damage from cellular oxidation including, “…atherosclerosis, cancer, diabetes, rheumatoid arthritis, post-ischemic perfusion injury, myocardial infarction, cardiovascular diseases, chronic inflammation, stroke, septic shock, aging and other degenerative diseases in humans (Uttara et al. 2009).”

While humans don’t photosynthesize and therefore don’t have as much oxidation from excess oxygen in cells, they do produce large quantities of oxidants as a consequence of metabolizing their food. Recall that metabolism involves the shuffling of electrons between molecules. The process is messy, resulting in the production of some molecules that are missing an electron in their outer shell. These free-radicals cause damage to the cell’s molecular structure. The more people eat, the more free-radicals they create. Since free-radicals are so damaging to human health, people should choose plant centered diets rich in antioxidants (Prior et al. 2007; Matés et al. 1999).
The physics and chemistry of water determine the solubility of oxygen and gases. The concentrations of oxygen in the Chesapeake Bay fluctuate widely with time and location, ranging from zero to about 14 mg/l. Salinity reduces the solubility for oxygen in water, as it does for all gases. In essence, the salt molecules take up space otherwise used by dissolved gases. Increasing temperature also reduces gas solubility in water. Water, and for that matter all substances above absolute zero (much colder than any place on Earth), vibrates. The warmer the water, the faster the water molecules vibrate, and that leaves less effective room for gases to dissolve.

Now consider the combined effects of temperature and salinity. The cold and fresher waters found in the upper tributaries in spring can potentially contain twice the oxygen found in warm, salty waters near the mouth of the Bay in summer. Water is saturated with a gas when it can’t hold any more over time, with the excess forming bubbles that float to the surface. Cold fresh water of 1 °C (just above the freezing point of water) entering the Bay in early spring will saturate at 14 mg/l of oxygen. The warm 20 °C and salty (30 ppt) water near the mouth of the Bay in summer will saturate with 5 mg/l, or at nearly two-thirds less oxygen than the cold fresh water (Wetzel 2001). So, it is tougher for a fish to use its gills to extract oxygen from warm salty water than cold fresher water. But it gets worse! The metabolic rate of fish (and all living creatures) is proportional to temperature. That means that they require more oxygen at higher temperatures. For example, the striped bass (aka rockfish, Morone saxatilis) may live in the Bay year-round. Following the general rule of a doubling of metabolic rate for every 10 °C increase in temperature, a striped bass will require nearly four times as much oxygen at 28 °C in summer as it will at 1 °C in winter (Clarke and Johnston 1999).

Often water in the Bay is either undersaturated or supersaturated with oxygen. Biology plays an important role here. Recall that one of the three ways oxygen gets into the Bay is by photosynthesis. Under the right conditions, the algae or sea grass in a portion of the Bay may be so stimulated with light and nutrients, that it supersaturates the water with oxygen. Once the rate of photosynthesis subsides, the oxygen concentration will return to saturation as the excess bubbles away. Rapidly warming surface waters, say during a heat wave in the late spring, can also supersaturate the water. Recall that the newly warmed water can no longer hold as much oxygen and it will bubble away over the course of a day or two.

Supersaturation with oxygen rarely presents problems for life in the Bay, but under-saturation can be devastating. There are four ways oxygen leaves the water. (1) It can move out by advection, dissolved in water flowing into the ocean. (2) It can diffuse or bubble into the atmosphere. (3) Oxygen may react with chemicals in the water, like iron or sulfur, to be locked-up in rust or bubbled away as sulfate. (4) And most importantly, oxygen may be used and even used up in the process of aerobic respiration conducted by living organisms, as discussed above. The loss of oxygen to respiring organisms (primarily bacteria) is indeed the biggest challenge faced by the Chesapeake Bay today. This will be explored in more detail below and in Chapter “Reversing the Eutrophication of the Chesapeake Bay and Its People”.

The Chesapeake Bay and Its Watershed is an Ecosystem Recall the hierarchy of life presented at the beginning of the chapter. The Chesapeake Bay and its watershed constitute an ecosystem. The living (biotic) and nonliving components of the Bay and its watershed interact in a dynamic way to yield an ecosystem. The nonliving constituents of this system include sunlight, gases such as oxygen, nitrogen (N₂), and carbon dioxide; water; dissolved mineral salts; mineral particles (clays, silts and sands), and temperature. The living portion of the Chesapeake Bay ecosystem includes, viruses, bacteria, tiny cells of algae (phytoplankton), and various plants and animals of all sorts and sizes. Energy and materials from outside the system (inputs) are used and modified by these abiotic and biotic components of the ecosystem to produce various outputs. For example, the inputs of CO₂, water, plant nutrients, and sunlight result in the outputs of oxygen and blue crabs (Callinectes sapidus). Cleary a lot happens in the Bay to transform simple inputs into complex outputs like blue crabs!

All life in the Chesapeake Bay ecosystem depends directly or indirectly on photosynthesis to provide the energy that powers metabolism and builds the molecules needed to assemble cells. Sunlight intercepted by leaves of tall oak trees and fields of planted corn in the watershed, or by tiny algal cells drifting in the Bay, is used to power the process of photosynthesis. Only about 1% of the sun’s energy is captured in photosynthesis (Odum and Barrett 2005), but that is enough to support an abundance of life in the Chesapeake Bay and its watershed.

Photosynthesis makes simple sugars that algae and green plants turn into the variety of biological molecules needed to support life. Some of those molecules like sugars, starch and lipids store energy used to run the metabolism of the plant. Others form the very stuff of life, biomolecules used to build cells and organisms. So, photosynthesis provides both the fuel of life and the building blocks of its construction.

The main biomolecules of life belong to four different groups. (1) Carbohydrates (contain Carbon [C], Hydrogen [H], Oxygen [O]) range from simple sugars and starch to cellulose (think wood) and other strong complex fibers that support tall trees. (2) Lipids (C, H, O) are fats, oils, and waxes that store energy, form cell membranes, and some play the
role of chemical messengers (hormones) in organisms. (3) Amino acids (C, H, O, Nitrogen [N], Sulfur [S]) link together to form proteins. Proteins are the action molecules of life, involved in essentially all the chemical reactions in cells (metabolism) as enzymes, that regulate those reactions. (4) Nucleic acids (C, H, O, N, P) are modified sugars that play two major roles. First, they are used for transferring energy in metabolism (Adenosine Diphosphate and Adenosine Triphosphate, ADP and ATP). Second, nucleic acids string together in chains of DNA (Deoxyribonucleic Acids) and RNA (Ribonucleic acids) that contain the genetic code. The DNA is the library of life, storing the directions for making the proteins that organize the lives of cells and organisms.

Sunlight provides the energy for photosynthesis, but not the raw materials needed to store that energy or build the molecules of life. The air, land, and water provide the nutrients used by plants for those purposes. Ecologists classify those nutrients by the relative quantity that is needed by plants or animals. Macronutrients are those needed in large amounts. CHNOPS, or carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur are all required in large amounts. They form the backbone of the molecules of life (carbohydrates, lipids, proteins and nucleic acids). Micronutrients are needed in much smaller amounts. These include minerals such as potassium, copper, iron, magnesium, calcium, and zinc. Also required in small amounts and not manufactured by the cells are organic molecules called vitamins. For a plant or animal to grow, it needs to have a source of energy and all of its required macro and micronutrients. If one of these is in short supply, not enough for growth to occur, it is said to be the limiting factor. During the warmer months of the year the limiting factor for plant growth in the Bay is usually a macro nutrient nitrogen (N) or phosphorus (P). But in winter, it might be lack of sunlight or low temperature that is the limiting factor for plant growth.

All the molecules of life are built on a skeleton of C, H, and O atoms. Those three elements alone are sufficient to build carbohydrates and lipids. The addition of N and S is needed to produce amino acids for making proteins. Adding P provides the essentials for building nucleic acids that are used in making the genetic material and in energy transfer. The ratio of these atoms in the algae cells like those that form the base of the food chain in the Bay is roughly: 263 H: 106 C: 110 O: 16 N: 2 S: 1 P (Chen et al. 1996). So, a cell needs about 106 C atoms and 12 N atoms for every one atom of P. In unpolluted waters there is plenty of C available, but usually less N or P to satisfy the needed ratio for building algae cells. This means that unless purposely fertilized or accidentally polluted, a lack of N or P typically limits plant growth during the warmer months for the Chesapeake Bay ecosystem.

Most commonly N is the limiting nutrient for the middle and lower portion of the Chesapeake Bay ecosystem. This is true for forests and most croplands, as it is for plants and algae living in the water. That means that if one adds nitrogen in an easily absorbed form, like ammonia or nitrate, plant growth will increase. Farmers in the region know this very well, and as such fertilize their crops with nitrogen. Prior to the mid-twentieth century, farmers mostly used animal and plant manures that we call organic fertilizers today. Those organic fertilizers tended to remain in place when applied to fields. Organic fertilizers slowly released N & P as they naturally decayed over time. Although introduced early in the twentieth century, it wasn’t until after WWII, that artificial fertilizers began to replace the manures on a large scale. The new synthetic forms of nitrogen were easy to apply but tended to wash away with rain and irrigation. The wasted artificial nitrogen fertilizer finds its way through streams, rivers and groundwater into the Bay. There it stimulates the growth of algae, turning the waters of the Bay green, red or brown. The massive growths of algae are called blooms. As the blooms first form, they supersaturate the water with oxygen released from photosynthesis. But soon, the algae sink and die, being eaten and decomposed by bacteria. The rotting blooms fuel massive bacterial respiration that depletes the water of oxygen. This process of over-fertilizing the Bay with nutrients, the subsequent algal bloom, and ultimate depletion of oxygen is called cultural eutrophication. As detailed below and in subsequent chapters, cultural eutrophication is the main agent degrading the Chesapeake Bay.

Why is nitrogen so important to plant growth? It is one of the micronutrients, being essential to the construction of proteins and nucleic acids. And it is hard to acquire, despite N₂ (elemental nitrogen) being the dominant gas in the atmosphere (78%). N₂ is held together by a triple covalent bond, meaning that it takes a lot of energy to break it apart and reconfigure it to become NH₄ or NO₃, the forms easily taken up by plants. Chapter “The Journey from Peruvian Guano to Artificial Fertilizer Ends with too Much Nitrogen in the Chesapeake Bay” will explain much more about the role of nitrogen in the Chesapeake Bay ecosystem.

**Food Chains and Food Webs** Energy flows through the Chesapeake Bay ecosystem along food chains and food webs. The food chain is a simple way of thinking about energy flow in ecosystems. Each of the steps in the food chain is called a trophic level. The chain starts with primary producers, the green plants and algae that use photosynthesis to change energy from sunlight into the chemical energy of biomolecules. Some of these primary producers are consumed by primary consumers, which in turn are eaten by secondary consumers, which are eaten by tertiary consumers.
Decomposers constitute a trophic level adjacent to all the consumer levels in the food chain. Decomposers consume the dead bodies and fragments of producers and consumers. Such dead material is termed detritus, and the organisms that feed upon it are called detritivores. Detritus nourishes a wide range of organisms, from bacteria and fungi to worms, blue crabs and gulls. Decomposers play a critical role in recycling nutrients, making the basic elements (primarily N and P) of life available to sustain the growth of primary producers. That is, decomposers get their energy from breaking down biomolecules and in the process regenerate nutrients for use by primary producers.

As a general rule, only about 10% of the energy available at one trophic level moves up the food chain to become available at the next trophic level. Energy is lost between trophic levels for several reasons. First, the second law of thermodynamics deems that some useful energy is lost every time energy is transferred from place to another. Second, only a portion of what a consumer eats is digested and absorbed into its body. If consumers only dined on simple sugars and lipids, then almost all of what they ate would be absorbed. But food items often contain such things as hard to digest plant fibers or animal shells. For humans, think of the difference in available calories between 100 g of each; glazed doughnuts (426 kcal), ground beef (295 kcal), and kale (49 kcal) (USDA 2018). Energy is also lost between trophic levels because consumers must use a portion of what they eat to keep themselves alive and do such things as move, defend themselves, seek mates, and reproduce. Homeothermic (warm blooded) consumers like birds and mammals spend much of the energy they consume on producing heat to stay warm. Consumers also share a portion of their plate with the microbiome (bacteria) in their guts.

Consider the energy loss along one important food chain of the Chesapeake Bay assuming the 10% efficiency rule. Suppose that one kg of algae floating in the Bay is consumed by the suspension feeding (filter feeding) fish called menhaden (Brevoortia tyrannus). That would result in 0.1 kg of menhaden flesh. A striped bass that ate that 0.1 kg of menhaden would only add 0.01 kg to its own body mass. A bottlenosed dolphin (Tursiops truncates) that ate 0.01 kg of the striped bass would only add 0.001 kg to its own body. By the time the 1 kg of algal biomass passed up the food chain to the dolphin, only 0.1% would be left. Another way of looking at this is that each 500 kg bottle-nosed dolphin would have to have eaten 5000 kg of striped bass, which would have to had consumed 50,000 kg of menhaden, which in turn ate 500,000 kg of algae! Alas, bottle-nosed dolphins tend to eat lower on the food chain, eating more menhaden than striped bass, but it is clear that food chains can only be four or five steps long before the energy is all but gone.

To be fair, aquatic food chains tend to be more efficient than their terrestrial counterparts, with closer to 20% efficiency of energy transfer between trophic levels. Nevertheless, the vast majority of energy stored at one trophic level will never reach the one above.

Eating lower on the food chain means more energy (food) is available to be consumed. This is as true for humans as it is for fish and dolphins. It takes about 10 kg of plant food to produce 1 kg of beef. So, it takes about the same amount of land to produce one beef burger as it would ten veggie burgers of the identical mass. Animal based foods account for about 30% of the calories consumed in the SAD (USDAERS 2016). Assuming all food was from land, this means that the animal food component accounts for about 3.3 times as much land use as is needed for the rest of the SAD which is based upon eating plants.

Food chains are handy ways of thinking about energy flow through the ecosystem. But in reality, most consumers are not restricted to eating just one particular plant or animal or at one particular trophic level. Omnivory, eating multiple types of species is the rule rather than the exception. Animals will choose different dietary items depending on relative availability, feeding preference, energetic reward, season, and life cycle. For example, striped bass appear to prefer menhaden to most other prey choices. The oily menhaden is a dense source of calories. Yet over-fishing of menhaden has driven a shift to eating the less nutritious blue crab (Callinectes sapidus) (Uphoff 2003). Thus, a food web better depicts the energy relationships between species than a simple food chain (Fig. 8).

There are different types of food-chains in the Bay. To understand them, it is important to grasp a bit of basic terminology that describes lifestyles of species. Plankton refers to the microbes, plants and animals that drift in the waters of the Bay. Some members of the plankton simply float along with the water currents. This is true of many of the algae that constitute the phytoplankton (plant-like plankton), as well as the microbes that make up the viroplankton and bacterioplankton. Others can swim and control their vertical distribution in the Bay, but are not strong enough to resist the horizontal currents. The Atlantic stinging nettle jellyfish (Chrysaora quinquecirrha), copepods, and the larvae of oysters are examples of such swimming zooplankton (animal-like plankton). Almost all of the living creatures of the Bay spend at least the beginning portion of their life cycles in the plankton, even if they grow up to live elsewhere.

The nekton refers to the good swimmers of the Bay. Examples include fish, blue crabs, turtles, and dolphins.
but the dolphins start their lives in plankton but mature into the nekton.

*Benthic* plants and animals live on the bottom of the Bay, from shallow marshes to the deepest channels. Sea lettuce (a leafy algae), oysters, blood worms, and snails are all members of the benthos as adults but begin life in the plankton.

The most familiar food chain goes like this: phytoplankton > zooplankton > small fish > big fish. One benthic food chain goes this way: phytoplankton > oyster > fish or bird. Another benthic food chain goes as follows: detritus > bacteria > worms > blue crabs or fish > big fish.

One critically important but often overlooked food chain in the Bay is called the microbial loop (Fig. 9). This one goes dissolved organic carbon (DOC) > bacteria > protozoans (single-celled animal like) > copepods > small fish > big fish. The microbial-loop food chain helps sustain the large populations of planktonic, benthic and nektonic creatures of the Bay. It utilizes the dissolved organic products of decomposition that wash into the Bay from the watershed and those created in the Bay proper. Algae, plants and animals all leak DOC into the water. Although one can’t see it, DOC is the largest pool of biomolecules in the Bay. In other words, if one were to take a square area of the Bay and add up all organic matter in the plankton, nekton, and benthos, it would be less than the DOC in the water under that same patch! The millions of bacterial cells per milliliter (ml) feast on the abundant DOC, and thus making this invisible resource available to the rest of the food chain.
The role of bacteria and the importance of the microbial loop were only recently understood, beginning in the 1970s. Likewise, physiologists are only now grasping the importance of the microbial community that lives in the guts of humans. For example, a healthy human microbiome in the large intestine converts dietary fiber to small chain fatty acids necessary to feed the cells in the walls of the colon (Possemiers et al. 2011; Sonnenburg and Sonnenburg 2014). Since omnivory is the rule, the feeding relationships in the Bay are best thought of as a food web that links all plants and animals together to greater and lesser degrees. The complex food web of the Bay helps make for a stable ecosystem. If one species is diminished, say Atlantic croaker (Micropogonias undulatus) for example, it may be replaced in the diets of predators by a similar fish such as spot (Leiostomus xanthurus). However, the stability of the food web breaks down with large fluctuations in the populations of certain key species. For example, the over exploitation of oysters for the food system during the twentieth century had dramatic effects on the quality of water in the Bay and the populations of other species that either feed on the oysters or used the oyster reefs as essential habitat. This will be explored in depth in Chapter “The Chesapeake Bay Oyster: Cobblestone to Keystone”.

Food chains are important to the understanding of how energy moves through the ecosystem. But they are also essential to understanding what governs the size of populations. Recall the discussion of limiting factors earlier. The underlying assumption is that all populations are limited in their size by whatever resource or condition is preventing further growth. This is called bottom up control. An example of bottom up theory is as follows: adding more nitrogen to the Bay promotes the growth of more phytoplankton, which then causes an increase in zooplankton, which promotes the growth of small fish that means more food for larger fish.

If populations of plants and animals were only controlled by the energy available from the trophic level below, then it would not matter how many fish, crabs, or oysters we took from the Bay. Yet we know from years of overharvesting that populations can certainly be controlled from the top of the food chain. Top down theory says that a consumer can control the size of the population in the trophic level below, and that the effect can cascade all the way down the food chain.

A once touted example of top-down control in the Chesapeake Bay is provided in the food chain that goes phytoplankton > oysters > cownose rays (Rhinoptera bonasus) > cobia (Rachycentron canadum) and sandbar sharks (Carcharhinus plumbeus). It was thought that overharvesting of cobia and sharks in the Bay enabled an increase in the population size of cownose rays. The increased ray population supposedly meant more predation on oysters and other mollusks (Myers et al. 2007). Yet more recent research casts doubt on this cascade, exonerating cownose rays for failures of oyster recover efforts (Grubbs et al. 2016). Nevertheless, there is no doubt that humans exerted sufficient top down control through fishing as to drastically reduce key populations in the Bay.

The consequences of over-harvesting seafood from the Bay will be explored in Chapter “A Fishing Trip: Exploiting and Managing the Commons of the Chesapeake Bay.”

One way to understand the health of the Chesapeake Bay is to compare the relative size of current populations with those of earlier times. The contemporary population size of oysters is about 1% of what it was in 1900. In contrast, the population size of various species of phytoplanktonic algae is many times that of earlier days (NOAA 2019).

Given unrestricted resources and the right conditions, all populations are capable of very rapid exponential growth. This is especially true of small species capable of quick reproduction. Consider phytoplanktonic algae in the Bay. During the long solar days of summer, the water is warm
Biodiversity  In his Map of Virginia, Capt. John Smith used the term “diverse” seven times in describing the natural wealth of the Chesapeake Bay and its environs (Smith 1612). This suggests that he understood the importance of variety in nature. Biodiversity is a hallmark of stable and productive ecosystems. Each different species of plant, animal, and microbe functions in the processing of energy and chemicals. They also work together in a complex set of interactions that sustains the integrity of the ecosystem over time, enabling it to endure predictable cycles of nature, such as seasonal change, and less frequent but intense situations such as fires, extended droughts, and severe storms.

Some species create living space and conditions for many others. The reefs built by generations of oysters (Crassostrea virginica) provide habitat and food for a variety of fish, birds, crabs, sponges, worms, and numerous other species (Gedan et al. 2014). The same is true for the beds of underwater plants created by eel grass (Zostera marina), that blanketed the shallows of the lower Chesapeake Bay during Capt. John Smith’s time (Lefcheck et al. 2017). The oyster reefs and grass beds provide the important ecosystem function of cleaning the water. The oysters remove excess algae and sediments from the water. The eel grass beds slow water movement, causing particles to settle, and take up excess nutrients from the water. Since their presence is so important for the viability of the ecosystem, the oysters and eel grass are termed foundation species.

In addition to celebrating the natural biodiversity of the region, Capt. John Smith noted how the Indians applied diversity in planting their crops. “In May also amongst their corne they plant Pumpeons, and a fruit like unto a muske millen, but lesse and worse, which they call Macocks. These increase exceedingly, and ripen in the beginning of July, and continue until September. They plant also Maracocks a wild fruit like a lemmon, which also increase infinitely (Smith 1612).” The Algonquin mimicked nature with a system of polyculture (many species), planting a variety of species together. They knew the corn stalks provided support for their climbing and clinging beans, but probably didn’t understand that the beans enriched their garden by providing the service of nitrogen fixation (See Chapters “The Algonquin Food System and How it Shaped the Ecosystem and Interactions with the English Colonists of the Chesapeake Bay and The Journey from Peruvian Guano to Artificial Fertilizer Ends with too Much Nitrogen in the Chesapeake Bay”).

The decedents of the colonists, and others that followed later, seemed to have lost their faith in the variety of life revered by their Algonquin predecessors. This is evident in the chemical-industrial agriculture so widely practiced in the watershed since the mid-twentieth century.

Monocultures (single species, often genetically identical) now occupy great swaths of land, planted all at the same time in uniform rows to accommodate farm machinery, and all harvested at the same time. Monocultures are virtually absent in nature, as they are inherently unstable, and soon overtaken by insects, rodents and other consumers. They also lack the services of nutrient recycling and soil protection that would be provided by neighboring species. As such, agricultural monocultures require massive inputs of energy, fertilizers, pesticides and water to produce a useful harvest. Chapters “A New Food System for the Chesapeake Bay Region and a Changing Climate and An Organic-Based Food System: A Voyage Back and Forward in Time” address the problems of monoculture and alternative forms of agriculture that embrace biodiversity.

Pollution and Cultural Eutrophication of the Bay and Its People  Pollution of the Chesapeake Bay ecosystem takes various forms, much of which traces directly or indirectly to our food system. Excess nutrients and organic matter drive cultural eutrophication. This process is a growing problem around the world, causing coastal dead zones of low oxygen in the Gulf of Mexico and over 400 other locations (Diaz and Rosenberg 2008). As noted above, excess nutrients from agriculture and human sewage promote the rapid growth of phytoplankton. When the algae die and sink to the bottom waters, they are decomposed by bacteria, which use all or most of the available oxygen in the process. Organic waste, such as those found in sewage, animal manure, or from paper mills, also get attacked by the oxygen consuming bacteria. Cultural eutrophication is responsible for the annual occurrence of the dead zone in the Chesapeake Bay, where oxygen levels are too low to support higher forms of life such as fish, crabs and oysters (Hagy et al. 2004, Chapter “Reversing the Eutrophication of the Chesapeake Bay and its People”).

Plastic bottles, bags, and food wrappers are solid waste pollutants (See Chapter “Plastic Pollution and the Chesapeake Bay: The Food System and Beyond”). Agricultural pesticides are toxic pollutants, causing harm to the human and non-human inhabitants of the ecosystem (See Chapter “Pesticides Bring the War on Nature to the Chesapeake Bay”).

We can think about pollutants as contaminates of water, land, and air, which is true. But we should also recognize that
most pollutants are misplaced resources. For example, animal manures are a valuable resource when used properly on agricultural lands for restoring fertility to the soil. But when misplaced by our food system into the Chesapeake Bay, they create cultural eutrophication.

The process of cultural eutrophication by the addition of excess inorganic nutrients provides too much nutrition, and the wrong kind of nutrition for the Bay to be healthy. Since the extra nutrients that feed eutrophication come from the watershed, which is outside the Bay proper, they are called allocanthous. This is different from the autohanous nutrients that are recycled within the Bay. For example, oysters secrete ammonia (NH₄) as a waste product from digesting algae they have eaten. That released nitrogen may then fertilize other algae, sustaining the ecosystem through natural recycling of nutrients.

Another type of allocanthous input originating from the watershed is organic matter (detritus). Some is in the form of dead and decaying plant matter, mostly leaves and pieces of wood. Decaying marsh plants are an important source of detritus in the Bay. Detritus is different from the inorganic nutrient pollution mentioned above. It is made mostly of plant fibers like cellulose and ligands that are difficult to digest and decompose. It is much like what constitutes a high fiber diet for humans. While such detritus does contain some nitrogen, it is in a very low proportion to the carbon in its molecules. It takes weeks or months for detritivores, bacteria, and fungi to decompose this fibrous material. So, the nitrogen in the plant detritus is released more slowly than the pulses of inorganic nutrients that are washed in from farmers’ fields. The slow nutrient release from natural detritus doesn’t cause the extensive algal blooms linked to inorganic nitrogen released from industrial agriculture.

Humans also add a big helping of processed sewage to the Bay. Native Americans and colonists traditionally urinated and defecated on the land. That kept the organic matter and nutrients in the soil. The growth of towns and cities in the watershed coupled with the adoption of the flush toilet in the mid-nineteenth century changed this, with human excrement carried in pipes to the nearest river. Prior to the advent of wastewater treatment plants in the second half of the twentieth century, sewage flowed directly into tributaries of the Bay. The raw sewage provided a feast for waterborne bacteria, their respiration drawing down the available oxygen. The sewage also contained pathogens that caused dysentery other diseases, and forced the closing of prime oyster grounds due to contamination.

These days, most of the organic matter of sewage is digested and collected as biosolids (sludge) at wastewater treatment facilities that dot the coastlines of the tributaries draining into the Bay. However, the decomposition process at the treatment plants, which do an excellent job of removing excess organic matter and killing pathogens, still releases large quantities of nitrogen and other nutrients to the Bay, adding to cultural eutrophication. Improved ways of treating sewage are addressed in Chapter “Finishing the Journey: Wastewater as a Misplaced Resource”.

It is not just human feces and urine that contributes to cultural eutrophication of the Bay. Our current food system relies on highly concentrated facilities to feed chicken, pigs, and cattle. These Concentrated Animal Feeding Operations (CAFOs) house thousands of animals on small plots of land that produce tons of waste daily. Much of the organic matter and nitrogen from those wastes wash into the Chesapeake Bay, contributing to cultural eutrophication. This is be covered in Chapters “The Journey from Peruvian Guano to Artificial Fertilizer Ends with too Much Nitrogen in the Chesapeake Bay and Livestock and Poultry: The Other Colonists Who Changed the Food System of the Chesapeake Bay”.

The cultural eutrophication of the Chesapeake Bay is closely linked to our food system. That same food system which is driving cultural eutrophication of the Bay is having a similar effect on the human residents of the watershed. As with the Bay, too much of the wrong kinds of nutrition produced by the food system is making people sick. The Standard American Diet (SAD) drives obesity, heart disease, diabetes, and a whole host of other human diseases. Toxins Pollution from nutrients and organic matter are detrimental, but generally not toxic. Indeed, they promote the growth of lifeforms such as algae and bacteria and as such imbalance the ecosystem. A consequence may be oxygen depletion, which is lethal to many animals. But excess nutrients and organic matter pollution aren’t directly deadly.

In contrast, insecticides and herbicides are designed to kill insects and weeds, so naturally they can kill or sicken animals in the Bay. Thanks to water pollution laws, releases of toxins that outright kill fish and other animals in the Bay are rare events these days. However, the widespread use of a variety of pesticides in our food system still creates problems for many species, such as lower birthrates or changes in behaviors. Acute toxicity is generally deadly or highly damaging. Chronic toxicity does not kill outright but diminishes the health of affected populations. This is true for fish in the Bay such as striped bass, as well as for the people that eat the fish (MD Fish Consumption Advisory 2014). Mercury is a common chronic toxin in predatory fish of the Bay. Among other things, mercury diminishes the function of the nervous system, something to think about as long you still can, if you are eating too much fish. Mercury enters the Bay primarily
as a byproduct of coal burning to produce electricity. A significant portion of that electrical energy is used to subsidize our food system, from production of fertilizers, to refrigeration and food processing.

Atrazine is a very widely used herbicide designed to kill broadleaf plants by disrupting their photosynthetic system. Since animals don’t photosynthesize, this is not a problem for them. Yet, Atrazine disrupts the endocrine system in animals, interfering with the activity of hormones critical for development and organ system functioning. It also causes cancer in mammals, including humans (Fan et al. 2007). So, chemicals may be toxic in one way for one species, and in another way for a different species.

To understand the distribution of toxic substances in the Bay, one must appreciate the role of biological magnification of materials up the food chain. Recall that water is polar and that nonpolar substances can dissolve in it, but only to a limited degree. Many toxins have limited solubility in water and quickly move from water into living cells, be they cells of bacteria, crabs, or fish. Often the cells have limited ability to either degrade or excrete the toxin, so it tends to stay put in the living tissue. Consider mercury. It may enter the Chesapeake Bay in the elemental form from the atmosphere as a consequence of burning coal. Being heavy the mercury quickly sinks to the sediments. There, in the absence of oxygen, it is changed to methylmercury, which enters bacterial cells. Millions of those bacteria are consumed by a worm which ends up storing the mercury in its tissues. A small fish like an Atlantic croaker (Micropogonias undulates) might eat that worm and hundreds of others like it, retaining most of the mercury in its tissues (Gilmour and Riedel 2000). A striped bass that ate 100 croakers would retain most of the mercury from its meals. An angler that ate the striped bass would get its full load of concentrated mercury. This is why authorities warn against eating more than one or two servings of striped bass a month. To summarize, biological magnification concentrates toxins at ever increasing levels with each step in the food chain. The reader will learn more about toxic substances in the Bay in Chapter “Pesticides Bring the War on Nature to the Chesapeake Bay”.

Exotic parasites often devastate native species lacking any history of coevolution. MSX (Haplosporidium nelsoni) kills the native eastern oyster (Crassostrea virginica) and appears to have arrived in the region in plantings of the Pacific oyster (C. gigas) imported from Japan. If so, this is an unintended consequence of an attempt to alter the local food system (Hagan 2018).

Perhaps 90% of the Native American population in North America was wipedout by infectious diseases brought by Spanish explorers and colonists (Walbert 2016). Most of those pathogens came from the European food system that utilized livestock: birds, cattle, sheep, and pigs. Measles, smallpox, influenza, diphtheria, the common cold, and tuberculosis all trace to animal husbandry. The Europeans had coevolved with these zoonotic (of animal origin) diseases, but for the Native Americans, the pathogens were all newly introduced species for which their immune systems were unprepared. These diseases of the European food system were so potent that they spread faster than conquistadores could carry them. Some scientists suggest that the Algonquin of the Chesapeake escaped most of these devastating diseases due to their relative isolation and habit of migrating between agricultural settlements and hunting/fishing camps on a seasonal basis (Rountree et al. 2007). The Covid-19 pandemic of 2020 originated with exotic animals (bats) captured for food.

**Circulation in the Bay and Human Bodies** The circulation of fluids in humans is essential for good health. The same is true for the circulation of water and the health of the Chesapeake Bay. For both humans and the Bay, circulation provides nutrients and oxygen where needed and removes waste products.

The heart is the main driver of circulation in the human body (Fig. 10). The pumping heart ensures that the cells of the body are constantly supplied with oxygen, and food, while being relieved of waste products like CO₂ and ammonia (NH₄). The right side of the heart collects blood from all over the body and sends it to the lungs where it refreshes its supply of oxygen and releases much of its CO₂. The oxygen-rich blood returning from the lungs enters the left side of the heart where it is pumped back to the rest of the body.

Human bodies have sufficient reserves of nutrition to survive weeks without eating but starved of oxygen people die within minutes. A stopped heart leads to sudden death. Heart failure is most often a result of clogged cardiac arteries that supply the heart muscle. The clogging is from deposits of cholesterol originating from the consumption of animal-based foods, the center of the SAD. Cholesterol is essentially absent from plant-based food. While people do make cholesterol themselves, it is those consuming the extra dietary cholesterol that develop heart disease and consequently die of cardiac arrest.
There is no heart to supply the force for circulating the waters of the Chesapeake Bay. Yet the SAD that interferes with the supply of oxygen in the human body is based on a food system that also interferes with the supply of oxygen in the Bay, as will be illustrated below.

Absent a pumping heart, gravity and wind do the work of moving the Bay’s waters. Gravity circulates water in the Bay by two different means, driving tidal flow and as a component of the hydrological cycle.

First, consider the tides. The moon and the sun both exert gravitational force upon the Earth. It is most evident in the coastal sea as the gravitational forces from those celestial bodies cause the water to slosh back and forth in the various ocean basins. A flooding tide is one that moves water into the Chesapeake Bay from the Atlantic Ocean, resulting in a high tide. This is followed by the ebbing tide of water moving back to the ocean and resulting in a low tide. The brief periods of an hour or so between flooding and ebbing is called slack tide. The tidal rhythm of the Bay is called semi-diurnal, meaning that there are two high tides and two low tides each day of roughly equal tidal height. When the Sun, Moon, and Earth all fall in a line, the gravitational forces are additive, resulting in big swings in the tide, producing the highest high and the lowest low tides. These are called spring tides and happen twice a month, on the days around the new moon and the days around the full moon. When the moon, earth, and sun form a right triangle, the gravitational forces of the sun and moon are out of phase, producing neap tides of the least extreme between high and low. Neap tides occur twice a month around the times of the half-moons. A significant portion of the water in the Bay is moved on each tidal cycle, providing water circulation throughout the entire system. The time between a high and a low tide is about 6.5 h. For a portion of the Bay, where the average ebbing tidal velocity is 1 km per hour, a mass of water would move 6.5 km toward the ocean. The tidal flows also cause mixing on small scales, as along the bottom sediments and in marshes along the shores.

Now, consider the role of gravity in the hydrological cycle that feeds freshwater to the Bay. Energy from the sun evaporates water from land and sea. The gaseous water vapor easily floats into the atmosphere where it eventually condenses into clouds. The independent water vapor molecules collide together, forming new hydrogen bonds. The expanding molecules of water form liquid droplets, or when cold enough, crystals of ice. Gravity returns the water to the ground as precipitation (rain, snow, or hail). Some of that precipitation drains off or through the land and into the Bay via an extensive system of tributaries. The force of Earth’s gravity keeps the water moving down and out of the Bay into the Atlantic Ocean.

Recall that the freshwater draining into the Bay is less dense than the marine waters filling the estuary from the Atlantic Ocean. The lower density freshwater draining from the land floats on top of the saltier marine water from the sea. This divides the bay into two distinct layers, the fresher surface layer and the saltier deep layer. This layering is most distinct in summer when the surface water density is reduced by elevated temperature as well as low salinity. The seasonal formation of distinct layers is called stratification, and this has profound consequences for circulation of water in the Bay. During the warm months of the year, the two layers fit together like matching wedges. The marine salt wedge narrows as it moves up the Bay, while the terrestrial freshwater wedge narrows as it extends to the ocean. This creates the conditions for the pattern of estuarine circulation explained next (Fig. 11).

As the fresher surface waters journey toward the mouth of the Bay, their gravity-driven flow rubs along the saltier and deeper layer. This generates an internal wave that drives the saltier marine waters in the opposite direction, up the estuary. The boundary between the fresher surface and saltier deeper waters provides minimal mixing between the two layers. This

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**Fig. 10** The circulation of blood in the human body illustrating the pattern of relative distribution to various organs given as percent of flow. By CMG Lee. [https://upload.wikimedia.org/wikipedia/commons/d/dd/Sankey_diagram_human_circulatory_system.svg](https://upload.wikimedia.org/wikipedia/commons/d/dd/Sankey_diagram_human_circulatory_system.svg)
sets-up conditions for the deeper waters to be starved of oxygen by the time they complete their journey up the Bay.

The fresher surface water flowing out of the Bay is generally well supplied with oxygen. It has direct contact with the atmosphere, and it contains trillions of tiny algal cells performing photosynthesis during daylight hours, also adding oxygen to the water. But the deeper, cooler, saltier, and denser marine layer continues to sink on its way up the Bay. This means it is prevented from receiving oxygen from the atmosphere. In addition, little sunlight reaches the deeper water so there is essentially no photosynthesis to produce oxygen either. Despite arriving at the mouth of the Bay with a full load of oxygen, that supply is dissipated by bacteria and other decomposers eating dissolved and particulate organic matter. The food system that supplies the SAD makes the oxygen depletion worse by causing cultural eutrophication. The excess N and other nutrients from the food system that wash into the Bay stimulate blooms of algae in the surface waters. The algae then sink into the bottom waters of the Bay. Bacteria and other decomposers use oxygen in aerobic respiration as they feast on the rain of dead and dying algae. Now recall that the deeper marine waters are moving up the estuary, opposite to the freshwater layer above which is flowing out. This means that the residue of algal blooms fueling the oxygen-depleting bacteria is mostly retained in the Bay rather than being washed out to sea.

The cooling of the Chesapeake during fall and winter dissipates the strength of the stratification that forms in spring and summer. This allows for improved circulation of oxygen to the bottom waters and permits some flushing of excess organic matter into the Atlantic Ocean.

Winds also improve circulation of oxygen in the Bay. Winds create surface waves that increase the exchange of gasses with the atmosphere. Surface waves are the ones most people think of, the kind that make for a bumpy boat ride and that lap a shoreline. Sustained winds also create internal waves, ones not evident to the eye. These internal waves cause the different layers of the Bay to rock back and forth. With sufficient wind, the deep low-oxygen layer may rock so much that it is brought to the surface along the shore. That exposes the formerly deep water to the atmosphere where it can “catch a breath” and gain some oxygen (Scully 2010). However, when the low oxygen water first arrives at shore it stresses the animals living there. Blue crabs may crawl to the very edge of the water to escape the hypoxia. Coastal residents of the Bay call this a “crab jubilee” or “crab walk,” as it makes for easy capture of one of their favorite foods (Mountford 2008).

This discussion of circulation focuses on blood and lymph vessels in humans and river basins in estuaries simply as the conduits for flow. However, each is more than just a structure to contain the moving liquid. Both the vessels of the body and the basins of the Bay are living structures that perform a variety of functions critical to the health of their respective systems. Endothelium cells that line blood vessels regulate the passage of materials to and from the adjacent tissues they serve. They also play important roles in the immune and inflammation response (Mai et al. 2013) and endocrine system (Ingami et al. 1995).

The sediments and structures that line the shores and bottom of the Bay and its numerous tributaries are as alive as the walls of blood vessels. They support benthic communities diverse with life. Intertidal and shallow areas with sufficient light feature photosynthetic microalgae, seaweeds and vascular plants. Suspension feeders such as oysters, mussels, barnacles, and sponges clean the water of excessive phytoplankton and detritus. These intermingle with the digestive system of the Bay: detritivores (worms, crabs,
etc.), bacteria, and fungi. Fish and birds rely on the benthic community for sustenance and habitat.

The more circulation the better? More circulation means better delivery of oxygen and nutrients to human tissues and components of the Bay ecosystems. For humans, the consequence of reduced circulation include increased chances of heart attack, erectile dysfunction (Gupta et al. 2011), Alzheimer’s disease (de la Torre 2002), peripheral arterial disease (Rajendran et al. 2013), and lower back pain (Kauppila 2009). For the Chesapeake Bay, poor circulation coupled with eutrophication creates areas of oxygen depletion and means less food for suspension feeders such as oysters, mussels, and sponges. Yet, excessive circulation may cause problems for both humans and the Bay. For humans, cancerous tumors require the proliferation of additional blood vessels (angiogenesis) to support their growth and spread to other organs. Type 2 diabetes, a disease caused by SAD, too often leads to diabetic retinopathy where abnormal blood vessels proliferate on the light sensitive portion of the eye. This diet driven excess circulation is the leading cause of adult blindness in the US (NEI 2018). Excessive circulation also causes problems in the Bay. The heavy precipitation from large storms erodes the soils of the watershed, causing vast quantities of sediments and excess nutrients to flood into the Chesapeake. The sediments clog channels and the nutrients drive eutrophication. Flooding and storm driven waves often destroy marsh and beach habitats.

Subsidies of Energy to the Chesapeake Bay Ecosystem and Its People We usually think of the Chesapeake Bay ecosystem as being powered by sunlight working through the biological process of photosynthesis. Producers in the form of green plants and algae use photosynthesis to turn sunlight into chemical energy. The producers provide energy to the trophic (feeding) levels above, including the decomposers. The solar energy harvested by algae and marsh plants supports a food chain leading all the way through striped bass up to osprey and eagles. The photosynthesis of terrestrial plants including grasses and trees powers a food chain leading to owls and foxes. These sun powered food chains also nourished the Powhatan and the original colonists.

In addition to what’s provided by photosynthesis, the Chesapeake Bay ecosystem requires other sources of energy to function. These other non-photosynthetic sources are called energy subsidies.

Sunlight that isn’t used for photosynthesis acts as an energy subsidy in several ways. The solar energy heats the water of the Bay, the soil, and the air, yielding a temperature regime suitable for the organisms of the ecosystem. The annual solar thermal cycle controls the activity of life on land and in the water. The metabolic rates of the plants, microbes, and most of the animals depend directly on the temperature. The warmth of spring awakens biological activity from winter’s cold-induced dormancy. While mammals, birds and a few fish can generate heat from metabolizing their food, the vast majority of life depends on solar energy to provide the temperatures needed for active living. The annual timing of the solar energy subsidy not only regulates the year-round residents of the Chesapeake region, but also determines the patterns of migration for its visiting fish and fowl populations. The Powhatan and other tribes on the Chesapeake planted their crops on fields they knew would warm quickly in springtime, and sunshine, and timed their hunts to correspond with animal migrations (Rountree et al. 2007). See Chapter “The Algonquin Food System and How it Shaped the Ecosystem and Interactions with the English Colonists of the Chesapeake Bay”.

Solar thermal energy works with gravity to provide another subsidy by powering the hydrological (water) cycle. Thermal energy from sunlight evaporates water from the salty ocean. This process produces essentially pure water vapor, cleaned of salts and other contaminants. When cooled, the vapor condenses into clouds. Eventually the clouds condense further, and the force of gravity returns the cleaned water to the earth in the form of rain, snow, or sleet.

Solar thermal energy and gravity also team to subsidize the ecosystem by creating wind. In the simplest of terms, wind is the flow of air from an area of high pressure to one of low pressure. This is true on the global scale as well as on the local level such as on the Chesapeake Bay. Gravity works on the mass of air to create pressure. Solar thermal energy warms a mass of air, causing it to expand and thus be of lower density. The lower density means fewer molecules of air, and therefore less atmospheric pressure. In contrast, air cooled such as by losing heat at night, will be of higher density and therefore of higher atmospheric pressure. Air will flow from areas of high pressure to area of low pressure, creating wind.

Capt. John Smith and subsequent sailors of the Chesapeake would all know well the predictable patterns of wind that blow across the Bay on clear days from spring to fall. The morning sun warms the land and the mass of air above it. By midday the warmed, low pressure air above the land begins to float skyward. It is replaced by a mass of cooler air coming from above the adjacent and colder Atlantic Ocean. This sea breeze flowing from the east appears most afternoons during the warmer months and persists till sundown. At night the land may cool enough to create a reverse flow from the west, called a land breeze.

Wind energy subsidizes the ecosystem in several important ways. As mentioned above, it drives surface and internal waves that play a role in circulating water in the Bay. Anyone
parking a car in the Chesapeake watershed during the spring knows of the wind-borne pollen from pines and oaks that covers their vehicle in a dust of green. Wind is an energy subsidy for plants that lack the services of pollinators such as bees. The wind also disperses the winged seeds of maple and beach trees, and the hairy ones generated by willows (Andersen 1991).

While solar powered photosynthesis feeds the food chain leading to osprey (*Pandion haliaetus*) and bald eagles (*Haliaeetus leucocephalus*), it is the subsidy of solar thermal energy that keeps these birds aloft (Fig. 12). The sunlight heats the atmosphere, causing rising columns of lower-density air (thermals). The osprey and eagles ride the thermals, reducing the energy expended in flapping wings while hunting or migrating (Katzner et al. 2015).

The solar subsidy that helps osprey and other fishing birds stay aloft, also enables the raptors to maintain the integrity of their wings for flight and swimming. After plunging into the Bay in pursuit of a meal, osprey, cormorant and other birds will perch atop a tree limb, pilling, or any convenient structure to dry their wings in the sunshine (Fig. 13). The solar thermal energy and breeze evaporates away the water, leaving the birds lithe for the next flight, and sufficiently buoyant to survive their next swim (Lippson and Lippson 2006). This solar subsidy also reduces the burning of their own energy reserves to power thermogenesis (metabolic production of heat) otherwise needed to evaporate the water from their wet feathers.

In the previous discussion of circulation, the reader learned how gravity from the moon and sun powers tidal currents. These predictable tidal currents provide an energy subsidy to the planktonic larvae of blue crabs and other animals. The crab larvae swim up from the bottom to ride the flooding tidal currents up the Bay. The larvae migrate back down to the bottom to avoid being washed back down the Bay by the subsequent ebb tidal current. Over the course of some days they use the energy subsidy of the flooding tide to make the 200 km (124 miles) passage up the Bay (Welch et al. 1999). They could never swim that far on their own.

The human population of the Chesapeake Bay ecosystem also benefits from the natural energy subsidies of wind, solar heat, and gravity. The Algonquin and the colonists relied on wind to pollinate their corn. Both took advantage of gravity driven tides to quicken their navigation of the Bay and to help trap migrating fish (See Chapters “The Algonquin Food System and How it Shaped the Ecosystem and Interactions with the English Colonists of the Chesapeake Bay and A Fishing Trip: Exploiting and Managing the Commons of the Chesapeake Bay”). The colonists took the gravity subsidy a step further, using impounded water to drive grist mills to grind their grain. Wind subsidies brought Capt. John Smith and company across the Atlantic Ocean and powered much

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**Fig. 12** A soaring osprey (*Pandion haliaetus*) takes advantage of a subsidy from solar energy that warms rising air masses. The energy saved on flapping wings is available for growth, reproduction, and other body functions. By Pete Markham from Loretto, USA. https://upload.wikimedia.org/wikipedia/commons/thumb/d/db/Pandion_haliaetus_-Sanibel_Island%2C_Florida%2C_USA_-flying-8.jpg/1024px-Pandion_haliaetus_-Sanibel_Island%2C_Florida%2C_USA_-flying-8.jpg
of the navigation on the Bay and beyond until the age of steam, two centuries later.

In recent times the residents of the Chesapeake region got better at using the natural energy subsidies provided by gravity, solar, and wind. As noted in Chapter “The Bay and Its Watershed: A Voyage Back in Time”, in the early twentieth century they built the Conowingo Dam to produce electricity from gravity and falling water. Three generations later, the residents began to use sunlight to produce electricity from photovoltaic cells arrayed in abandoned farm fields or atop buildings. Currently the region is moving very slowly to building offshore turbines to take advantage of the wind subsidy.

The early twentieth century saw the introduction of a new and unnatural energy subsidy to the Chesapeake Bay ecosystem. Humans began using fossil fuels to subsidize the food system. Fossil fuels ultimately do come from photosynthesis, but their formation took place over a time span stretching back millions of years. So, the use of these long stored products of ancient photosynthesis is considered a subsidy to the agricultural portion of the ecosystem.

Upon their death, organisms start to decompose. Decomposers such as bacteria and fungus quickly consume the easily digestible components of the dead cells, leaving behind more resistant portions. If that residue is buried in terrestrial or aquatic sediments it may lose contact with free oxygen and exist in an acidic environment. The lack of oxygen and low pH is inhospitable to most decomposers. Over time, the carbohydrates, proteins, lipids, and nucleic acids from these dead organisms are transformed into hydrocarbons to produce the familiar fossil fuels of coal, petroleum and natural gas. With a source of ignition these fossil fuels will combine with free oxygen (burn), releasing the stored energy that eluded decomposers millions of years before. The burning also transforms the carbon previously stored in the fossil fuels into carbon dioxide (CO₂), a greenhouse gas that warms the planet and acidifies the Bay.

Food produced in the modern industrial-chemical food system represents much more energy from fossil fuel subsidy than it does from recent photosynthesis. For every calorie of food produced, it takes about 10 calories of fossil fuel subsidy. The energy from a dinner created by the industrial-chemical food system is about 10% from recent photosynthesis and 90% from fossil fuels! The fossil fuels are used to run farm machinery, process the food, package it, and transport it. Fossil fuel is also used to make artificial nitrogen fertilizers, herbicides, pesticides and pump water to irrigate the land. If a fast food serving of hamburger, fries, and a milkshake seems oily, it should, as most of the energy comes from petroleum and other hydrocarbons (Pimentel and Pimentel 2003; Pimentel et al. 2008; Canning et al. 2017). Chapter “A New Food System for The Chesapeake Bay Region and a Changing Climate” examines energy subsidies in the Chesapeake food system in more depth.

In a very real sense, people consuming the SAD (Standard American Diet) produced by industrial agriculture are like conventional automobiles, getting most of their energy from fossil fuels. People also use fossil fuel subsidies for transportation and heating buildings. This means that fewer of the calories they consume are used in walking or bike riding, and in thermoregulation (using metabolism to create heat). Fossil fuel subsidies are distorting the food system and reducing human physical activity, which contributes to morbidity and mortality (Gremeaux et al. 2012).
The basic science reviewed in this and the previous chapter will provision the reader with sufficient background to undertake a voyage to understanding the interactions between the food system, the Chesapeake Bay, and its people.

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