WHERE THE RIVER MEETS THE OCEAN - STORIES FROM SAN FRANCISCO ESTUARY

EDITED BY: Peggy W. Lehman, Pedro Morais, Theodore Flynn and Frances P. Wilkerson

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WHERE THE RIVER MEETS THE OCEAN - STORIES FROM SAN FRANCISCO ESTUARY

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What is an estuary? Where do they occur? How do they work? Who lives there? And why are estuaries important to our planet? This collection will answer all of these questions and more.

Estuaries are places where fresh water from rivers moving downstream from the mountains mixes with salty water moving upstream from the ocean. Estuaries thus contain both fresh and salty water habitats (places) where many kinds of plants and animals can live and grow. San Francisco Estuary is the largest estuary on the West Coast of the United States and is home to millions of people, plants and animals. Our scientists have been studying all aspects of the San Francisco Estuary for nearly 50 years and we have 35 stories to tell about the people, plants, and animals in the estuary. We will tell you horror stories of how tiny poisonous plants and vampire fish kill other fish, and we have success stories of how conservation saves the lives of tiny mice in marshes and birds along the Pacific Flyway.

The Collection of stories is divided into six sections, so you can easily find the stories that interest you the most. The first section describes the many kinds of habitats in the estuary, including rivers, shallow bays, wetlands, and marshes, and what makes them a good home for plants, animals, and people. In the second section, the water quality scientists will describe how they use boats, special instruments, and new technology to determine whether the water is healthy for people, plants, and animals.

In the third and fourth sections we will tell stories about how plants and animals live in the estuary. Microbiologists will describe the tiny, microscopic plants and animals that live in the estuary, what makes them grow, how important they are as food for animals and why they are sometimes poisonous. Fish scientists will describe the many kinds of fish in the estuary and how we measure their growth, determine where they are, what they eat, and the ways they use both fresh and saltwater habitats to grow and raise their young.

In the fifth section, scientists will discuss how invasions of plants and animals from outside of the estuary have changed habitats and the survival of native plants and animals. Lastly, in the sixth section, we will share how scientists in the estuary are using new technologies and management actions to control invasions of unwanted plants and animals, increase the growth of native plants and animals, improve water quality, and restore habitats in the estuary.

Cover Image: Scientists in San Francisco Estuary routinely make measurements to determine the health of the plants, animals and water quality in the estuary.

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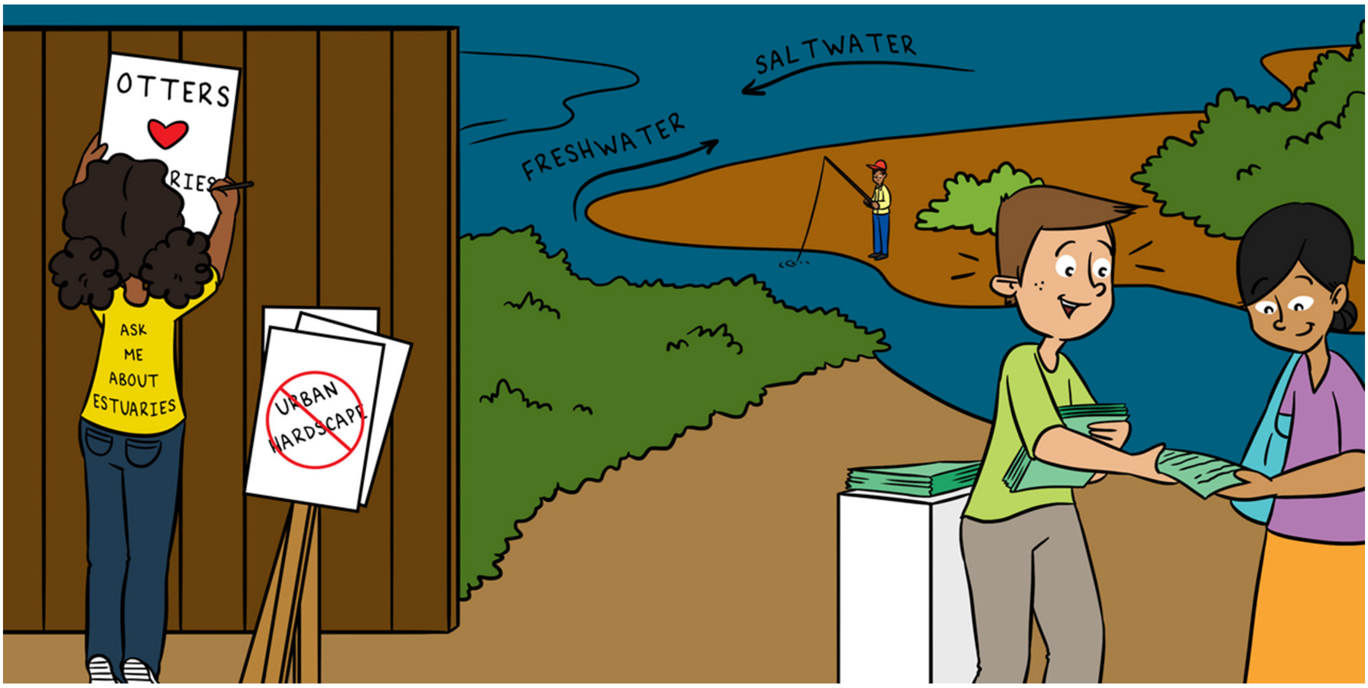

ESTUARIES, HUMAN BEINGS, AND THE FUTURE

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YOUNG REVIEWER:

GWEN
AGE: 13

Estuaries are places on the earth where rivers meet oceans. When rain and snowmelt drain off the land, the fresh water collects in streams and rivers and eventually makes its way to the ocean. At the same time, the ocean has tides that push salty water upstream into the rivers. This place, where rivers and oceans mix, is called an estuary. Estuaries contain many kinds of habitats that are home to plants and animals. Many people work and live in estuaries. In this article, I describe what makes estuaries interesting and important to plants, animals, and people. I also explain how these important areas are under threat from certain human activities.

WHAT IS AN ESTUARY?

An estuary is a place where streams and rivers mix with the ocean (Figures 1A,B). An estuary is special because it is partly a river, partly an ocean, but also a place where these two kinds of water meet and mix. In most estuaries around the world, there is a **salinity** gradient as you move oceanward, with saltier water near the ocean and freshwater in the upper reaches, near rivers. An estuary has tides like the ocean, so the height of the water changes every few hours due to the

SALINITY

The amount of salt in water. Freshwater has low salinity, and sea water has high salinity.

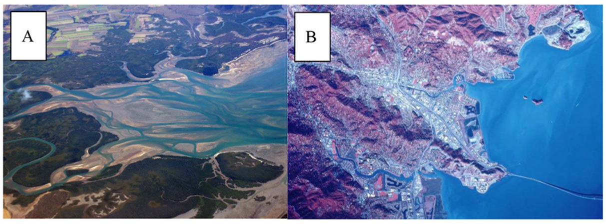

Figure 1

Figure 1

(A) Aerial photograph of the Murry River Estuary, Australia. This is a relatively undisturbed estuary, with some agriculture in the upper left of the photo (Permission for use granted via Creative Commons. Image credit: https://freeaussiestock.com/free/Queensland/slides/st_helens_beach_estuary.htm). **(B)** Satellite image of the Marin-Sonoma Counties Bay in California, showing extensive development within the San Francisco Estuary (roads and buildings are white or gray). This is an urbanized estuary, with much pavement and urban hardscape (Permission for use granted to the author. Image credit: http://www.krisweb.com/watershd/sanrafael_nasa.jpg).

gravitational pull of the moon as it circles the earth. Estuaries have rivers and creeks running through them too, so their water levels also change depending on how much rain and snow drains down to them. Estuaries have shallow parts and deep parts, muddy parts and clear parts. There are freshwater edges that have **marsh** plants, and very deep, dark, saltwater channels where sunlight does not reach the bottom. There is no place on Earth that has as many different habitats so close together as we find in an estuary.

Estuaries have also included people for a very long time, because humans like to fish, swim, and play in them. Many people live near or in an estuary, and estuaries are important places to store boats and goods moved between countries across the sea. For example, the Nile Delta estuary was likely populated by almost 2 million people before 3,000 B.C., and it is home to 39 million people today.

In this article, I describe several important facts about estuaries [1]. I think estuaries are special because of the different features we find there: physical, chemical, biological, and geological. An estuary is part stream, part lake, and part beach; it is partly fresh water and partly salty; it is partly land and partly water. An estuary is all these things all at once!

MARSH

A tract of low, wet land, often treeless and periodically flooded, generally characterized by the growth of grasses, sedges, cattails, and rushes.

WHERE ARE ESTUARIES?

Estuaries are commonly found on coasts. Water draining off the land finds its way down to the sea, usually flowing in large rivers. While there are small estuaries, most of the world's important estuaries are big, and are found at the end of long, large rivers like the Mississippi River in North America, the Nile River in Africa and the Middle East, and the Amazon River in South America. I live near the San Francisco Estuary in California, where one of the largest rivers on the west coast of the United States, the Sacramento river, washes into the Pacific Ocean. The San Francisco Estuary receives river flow from almost half of the state of California, including snowmelt and **runoff** from the Sierra mountains, 100 km or more from the Pacific Ocean (Figure 2).

RUNOFF

Something that drains or flows off, as rain that flows off from the land in streams.

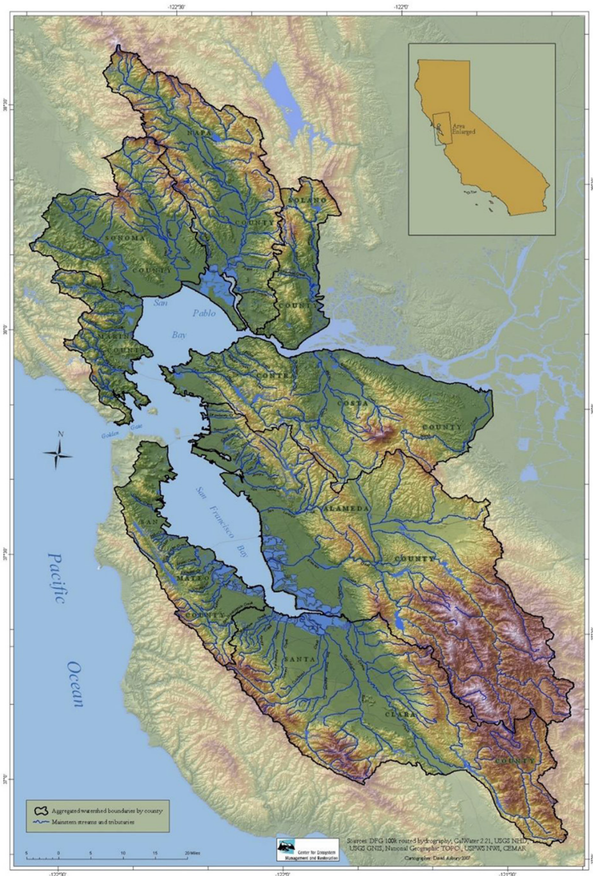

Figure 2

Figure 2

Map of the San Francisco Estuary and Bay Watersheds (darker-colored areas highlighted in black) from the Sacramento-San Joaquin Delta to the Pacific Ocean near San Francisco, California (Permission for use granted to the author. Image credit: http://www.cemar.org/steelhead_sfew.html).

WHAT PLANTS AND ANIMALS LIVE IN ESTUARIES?

Estuaries have habitats like those of oceans, rivers, **floodplains**, and lakes. Many estuaries also experience dry seasons with little rain or snow, and wet seasons with flooding and lots of mountain snowmelt and runoff. Many species can find habitats to their liking in estuaries. Therefore, estuaries are home to more species of plants and animals than almost any other place on Earth. For example, there are more than 500 species of fish and wildlife in the San Francisco Estuary! There are marine creatures that like to live in estuaries, and plenty of plants and animals from freshwater places also find homes in estuaries, as long as conditions do not get too salty for too long. Many organisms in estuaries are adapted to **brackish** water, like species of crabs, insects, fish, birds, snakes, and even otters. These organisms use the mixing zone of estuaries, where salt and fresh water come together, to raise their young or as a **migration corridor**. Well-known migratory species, like salmon and sturgeon, spend some time during their lives in estuaries, as they move from the coast or the ocean to the interior rivers and back again. Ducks and many other birds find resting places in estuaries during their long-distance migrations. So, it is easy to understand how so many plants and animals can be found in estuaries—there are many different habitats to fill.

FLOODPLAIN

A nearly flat plain along the course of a stream or river that is naturally subject to flooding.

BRACKISH

Slightly salty.

MIGRATION CORRIDOR

Routes followed by animals, birds, or fish when traveling between different habitats, as in salmon moving from the ocean to rivers to spawn.

DO PEOPLE HAVE AN EFFECT ON ESTUARIES?

People find it satisfying to live in or visit estuaries; swimming, boating, hunting, or fishing in an environment that is sometimes like the ocean and sometimes like the river. People have discovered they can use estuaries as places to build harbors and factories and still be near transportation services and nice places to live and relax. Put a different way, estuaries are places where we can find many **ecosystem services**, which are benefits that an ecosystem provides [2]. Easy access to drinking water, plentiful fish and seafood for eating and selling, large quantities of water to dilute pollution from factories or sewers, and readily available open land near the ocean—these are all reasons why people are drawn to work and live in estuaries. For example, owing to the nice weather and pleasant scenery near the coast, and because of the variety of ecosystem services available, almost 8 million people lived in or near San Francisco Estuary's shorelines and coasts in 2019 [3].

ECOSYSTEM SERVICES

The important benefits for people that arise from healthily functioning ecosystems, notably production of oxygen, creation of soil, and water purification.

People have been congregating in and interacting with estuaries for thousands of years [4]. Due to human activities, changes occur to river flow, tides, and the plants and animals that live in estuaries. Pollution accumulates, and huge quantities of water are captured and pumped elsewhere for drinking, agriculture, industry, and other uses. Civilizations have profited greatly from estuaries for thousands of years, and the health of our estuaries is connected to the health and wealth of the people who live, work, and play there.

Some people (like me!) choose to study estuaries to understand how they work. As scientists have noticed the negative effects that humans can have on estuaries, people have also decided to protect the estuarine wildlife and the habitats, by creating parks or reserves where estuaries can remain natural. Often, however, humans contribute to the degradation of estuaries by ignoring their value to society, and by doing things that contribute to the destruction of estuaries, like **infilling** or draining, or by building urban areas, roads, and ports.

INFILLING

To fill in with soil or sediment, as in the placement of soil to prepare for the construction of buildings.

WHAT WILL HAPPEN TO ESTUARIES IN THE FUTURE?

Global climate change and sea-level rise are affecting estuaries worldwide [5]. Ocean circulation and rainfall patterns are changing, land is sinking, and floods and droughts are more common in and around estuaries. Temperatures in many places are getting warmer over time, and normal weather is being replaced by unusually strong storms or changes in their frequency. All of these things imperil the habitats and ecosystem services provided by estuaries all over the world. In the San Francisco Estuary for example, many wetlands are getting squeezed between the rising ocean and the cities we have built right up to the edges of the estuary (Figure 3). The upper edges of

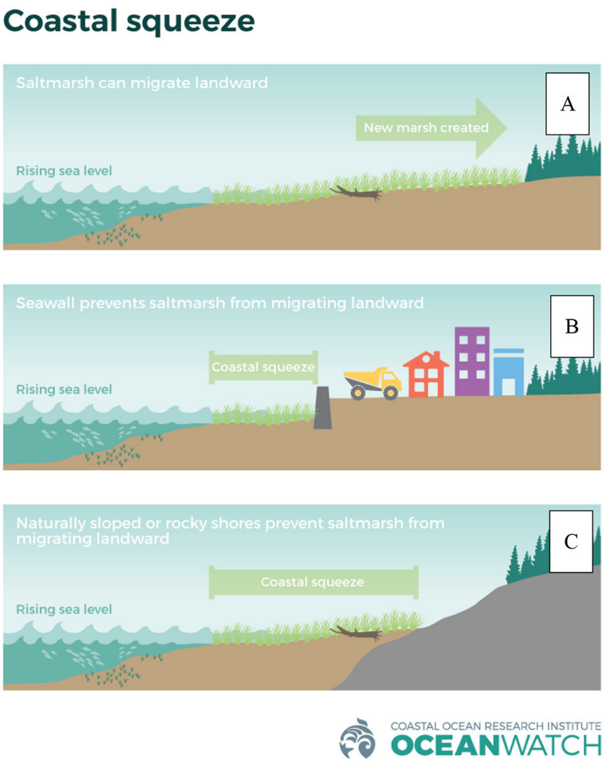

Figure 3

Figure 3

(A) Normally, as sea level rises, wetlands naturally progress higher onto the surrounding shore. **(B)** When people build seawalls and buildings near the shore, this creates barriers to the tides, and the marsh can no longer move inland. This is called coastal squeeze. **(C)** Coastal squeeze occurs naturally too, where rocks or steep slopes prevent landward movement of marshes (Permission for use granted to the author by the Ocean Wise Conservation Association. Image credit: https://oceanwatch.ca/howesound/wp-content/uploads/sites/2/2016/11/diagram-coastal-squeeze-BRANDED.png).

estuaries are at risk because the natural upward movement of estuaries is commonly blocked by manmade structures such as paved areas, buildings, roads, or railways. San Francisco Estuary's marshes are at risk of being flooded and drowned because they cannot move upward or landward as the sea level rises, the way they could before roads and buildings blocked their path. If these estuary habitats disappear, birds, fish, and crabs will have fewer places to live and they might be exposed to more pollution. If our cities get flooded more often, many businesses and people may have to move to places that are higher and drier, or they may have to pay more to repair damage caused by rising ocean tides.

There will always be an estuary between California's rivers and the Pacific Ocean, but where that estuary is or what it looks like—physically, chemically, biologically, and geologically—will change rapidly over the next 5 to 50 years. This is also true for other estuaries all over the world. How governments decide to regulate and protect estuarine environments will have ripple effects on fisheries and wildlife habitats far into the future. The health of our estuaries—and human health and wealth—lies in the balance we achieve between industry and commerce and the need to preserve natural open spaces, like estuaries. What we decide we want estuaries to look like in the future will be one legacy of our human history. You can choose to be part of building that legacy by learning about and talking with your friends about what makes estuaries so special and useful.

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CONFLICT OF INTEREST: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER

GWEN, AGE: 13
Hi, my name is Gwen, I live in the U.S. and play piano and volleyball. I am in 8th grade, and my favorite subjects are science, math, art, and Spanish. I love to read, particularly Sci-Fi novels and series (I am also a huge fan of Harry Potter). I am very excited to be working with Frontiers for Young Minds!

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Dr. Steven Culberson is an estuarine ecologist. His interests in water, habitats, and organisms led him to study how the physical and biological worlds come together to form ecosystems. *steve.culberson@deltacouncil.ca.gov

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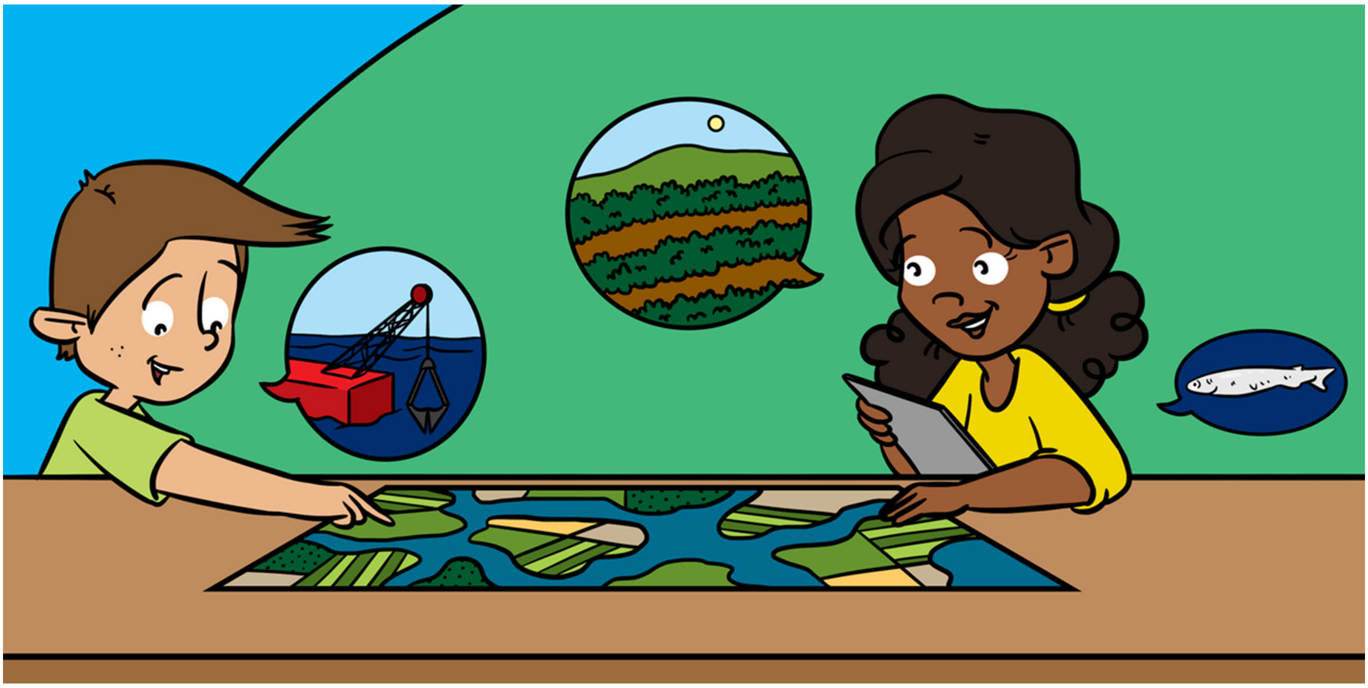

WE MAKE THE DELTA, AND THE DELTA MAKES US

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YOUNG REVIEWERS:

VIOLET
AGE: 9

ZORA
AGE: 10

The Sacramento-San Joaquin Delta of California was largely shaped, and is maintained by, an immense amount of human activity. Evidence of this activity can be felt everywhere in the Delta, from rock-lined levees to the straight channels, from the non-native fish and plant species to the amount of water that flows through the Delta and where that water goes. How the Delta looks, feels, smells, and functions also impacts the people who live, work, and play in the Delta, and who drink or eat crops grown with Delta water. This article will explore how people have made the Delta and how the Delta influences people's lives, both within and beyond this unique region.

WHERE TWO RIVERS MEET THE OCEAN

The Sacramento-San Joaquin Delta is part of the largest **estuary** on the west coast of North America, the San Francisco Bay Delta. This beautiful and unique water body formed where the Sacramento River and San Joaquin River join and flow into the salty San Francisco Bay.

ESTUARY

Where freshwater from a river and saltwater from the ocean meet and mix.

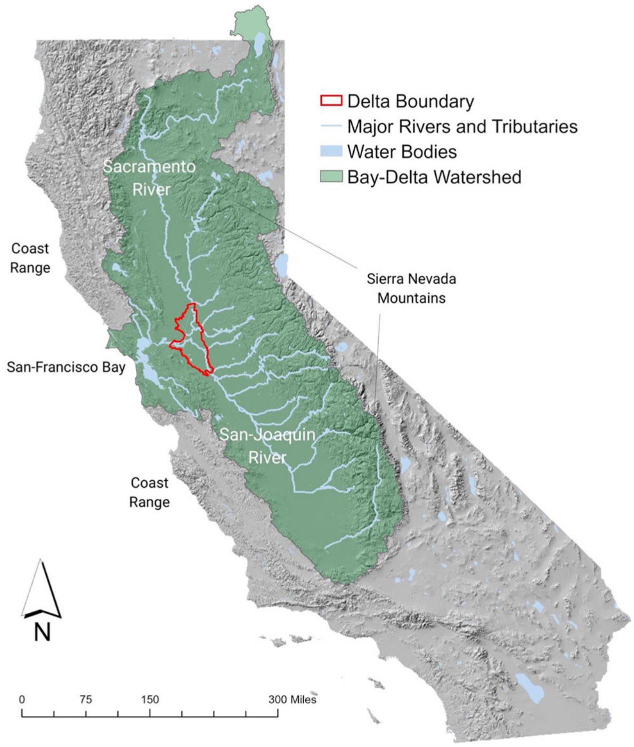

Figure 1

Figure 1

Map of California showing the Sacramento-San Joaquin Delta Watershed (Image credit: Alejo Kraus-Polk).

WATERSHED

Any area of land where rain or snow collects and drains to a common water body such as a lake, bay, or ocean.

SEDIMENT

Broken-down material carried by water or wind and deposited on land or the bottom of a water body such as a river, lake, bay, or ocean.

INVERTED DELTA

A less common form of delta, in which channels spread out and then reconnect at a narrowed outlet.

The Delta teaches us important lessons about how people change landscapes and how those landscapes change people.

The Sacramento and San Joaquin Rivers are the two largest rivers in the state of California. Their combined **watershed** covers nearly half of the state, including many smaller rivers and streams flowing out of the Sierra Nevada mountains and Coastal Range (Figure 1) [1]. The Sacramento-San Joaquin Delta refers to the area where these two rivers split into multiple smaller channels and meet—bringing water, fish, and **sediments** such as sand, silt, and gravel [2].

Deltas form as rivers slow down and empty water and sediment into an ocean, lake, or another river. As sediments in deltas build up over time, rivers must shift, and often split into many channels, giving deltas their typical fan shape. The Sacramento-San Joaquin Delta (or "Delta," for short) is different, in that it is a classic example of an **inverted delta**. After the rivers split into smaller channels, these channels meet again to flow through a single gap in the Coastal Range into the San Francisco Bay and, eventually, into the Pacific Ocean [2]. The Delta wasn't always like this. Fifteen thousand years ago, when sea levels were much lower during the last Ice Age, the Delta formed in what is now ocean, west of the San Francisco Bay. As sea levels rose over thousands of years, the Delta migrated toward its present location and became an inverted delta [3].

Figure 2

Figure 2

A modern delta levee, designed to keep rivers from flooding the surrounding lands (Photograph credit: Alejo Kraus-Polk).

California Indians lived through this significant change, but they had plenty of time to adapt. A large population of California Indians inhabited the Delta. These early inhabitants modified and maintained the Delta landscape through hunting, fishing, tending desirable plants, and intentionally setting fire to grasslands and forest understory to promote the growth of traditional food sources. California Indians continue to live in and around the Delta.

HOW IMMIGRANTS CHANGED THE DELTA

In the last 200 years, the Delta has been changed considerably by the activities of newly arrived people. The first wave of immigrants traveled through the Delta in the 1850s, seeking gold in the mountains [2]. However, the chances of striking it rich were small. Some people realized that farming Delta's fertile soils might be more promising. The problem was that the Delta was a naturally low-lying marshland and flooded nearly every winter. Sometimes the floods were so large that California's entire Central Valley would become a vast "inland sea" [4]. These floods made farming and building houses and cities a risky idea. However, the sediment deposited by floodwaters helped create the fertile soils that made farming in the region so attractive.

To make the Delta farmable required draining marshes and protecting these "reclaimed" lands from flooding. Immigrants from the Pearl River Delta in China, who had experience draining marshes for farming, did much of this work. They built **levees**, which are mounds of earth on the edge of rivers and channels, and they dug drainage ditches with shovels and wheelbarrows [5]. Unfortunately, big floods could easily undo all that hard work.

LEVEES

A wall of earth that protects cities and farmland from floods.

At first, there were no large machines to help, but eventually, large machines, such as the clamshell dredge, were invented. Machines made it possible to build larger levees that prevented floods from washing away farms and houses (Figure 2). The levees were made stronger by gravel washed down from the Sierra Nevada mountains, where hydraulic gold mining was taking place [5]. As the levees became stronger, people made more farms and houses and eventually cities, such as Sacramento, California's capital. However, building levees and draining marshes eliminated nearly all the habitat for the birds, fish, and mammals that had flourished there, either as year-round residents or seasonal migrants. The populations of these animal species, some of them unique to the area, fell significantly [3]. Meanwhile, the farmland area continued to increase, along with the sizes of nearby cities and towns [5].

Even though the levees were bigger, flooding was still a problem. When it snowed and rained a lot in the winter, there was not enough room in the rivers to hold the water. While the levees kept farms from flooding most of the time, they also made water levels in the river rise dangerously and, when levees broke, it was disastrous for the same farmland and towns the levees were built to protect [5]. In the early 1900s, the government built dams to capture snowmelt before it rushed into the rivers. The government also set aside areas where the rivers could flood, and no cities could be built [4]. The government also built some larger levees that were less likely to break, but these also increased the risk for those places with smaller levees.

MOVING DELTA WATER

The early 1900s also saw farming and cities growing in places far away from the Delta. Some of these growing areas, unlike the Delta, lacked the water necessary for living and working. Some places without enough water began pumping water from underground, but this was expensive, the water was sometimes salty, and sometimes the process even caused the ground to sink. People in these areas needed more freshwater, and they looked to the Delta.

Moving water from the Delta to far-away areas meant building long **aqueducts** and huge pumps, an expensive job that the government began in the mid-1900s. At first, it seemed like both the people in the Delta and those far away would be better off. However, once water could be moved from the Delta, the far-away areas became dependent on that water. During rainy years, cities and farms could get more water, and they began to expect the same amount of water even in drought years. Over time, it became clear that taking water from the Delta, especially in dry years, had damaging consequences for the Delta environment, including its cities, towns, and farms [1, 3].

AQUEDUCTS

An artificial channel for conveying water over a distance.

One significant consequence of taking fresh river water from the Delta is that saltwater from the San Francisco Bay flows in. This saltier water affects fish, plants, other species, and the farms, towns, and cities that rely on fresh Delta water. The huge pumps that move water from the Delta can also reverse the natural direction of the Delta's rivers, which can confuse the fish. In addition to the water pumped out of the Delta, water is taken out of the Sacramento and San Joaquin rivers before they reach the Delta, for use by upstream farms and cities. Some of

Figure 3

Figure 3

Critically endangered Delta smelt (Photograph credit: Peter Johnsen, U.S. Fish and Wildlife Service).

this water returns to the river more polluted, further threatening the fish and other users of Delta water [3].

Water has become a point of conflict between supporting the Delta's health and serving those outside the region who have come to depend on it. Many laws and programs have been put in place to balance those needs while also protecting the Delta's unique culture and character [2]. In addition to balancing water needs, these efforts also attempt to restore some of the lost habitats and fish species on the edge of extinction, such as the Delta smelt (Figure 3).

Today's Delta does not look, smell, feel, or function at all like the Delta that the first gold seekers encountered. The marshland—then one of the largest in North America—is almost entirely gone, along with fish, bird, and mammal life. New fish and plants have been brought into the Delta from far away. Delta channels that used to move around have now been straightened and fixed in place with rock-lined levees. The islands created by those channels have lost soil and sunk to below sea-level [2]. Where there once were riverside forests, there are now towns and cities.

HOW THE DELTA CHANGES PEOPLE

The Delta has not stopped changing. Now the process of changing marsh to farmland is being reversed. What is being farmed is changing as well, and new species continue to be introduced. As the variety and numbers of animal and fish species in the Delta shift, so do people's activities, such as boating, fishing, hunting, and wildlife viewing. Pollution remains a serious issue, but efforts to clean up the water are paying off.

Global climate change has already begun to affect the Delta. It is expected that impacts, such as sea-level rise, increased air and water temperatures, and changing river flows, will accelerate rapidly [2]. These changing conditions are already forcing people and other species to adapt. The California Indians adapted to major changes in the Delta as well. However, those changes occurred over thousands of years. Climate change will rapidly transform the Delta during your lifetime.

Adaptation in the Delta is much harder over such a short time span. One of the most challenging adaptations may come from sea-level rise, which will bring more salty water from the Bay and eventually flood Delta islands unless levees are continually enlarged [2]. It will be very costly to continue to pump water from the Delta, and the government is encouraging cities to reduce their dependence on Delta water.

CONCLUSION

The idea that humans have shaped the Delta and that the Delta shapes us is simple but powerful. We think this idea provides opportunities to think creatively, as we consider the far-reaching impact of how we might go about shaping the Delta differently. What emerges from this view of the Delta ecosystem is a broader question of how people create and affect environments that will, in turn, alter current and future generations. Today's Delta was shaped by people who wanted to change the landscape to support certain desired ways of living. Perhaps we now need to think about how people can change their desired ways of living to support a healthy and thriving Delta?

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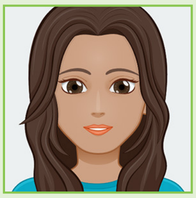
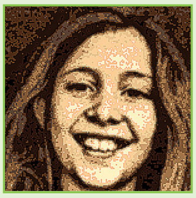
YOUNG REVIEWERS



VIOLET, AGE: 9

Violet loves reading and sharks, and hopes to either be a marine biologist or the President of the United States (or both!) when she grows up. Violet's favorite food is anything with cheese. In her free time she likes to play with her two dogs, Mochi and Pickles.



ZORA, AGE: 10

Hi, my name is Zora, and I enjoyed having the opportunity to review this article. I have many interests including reading, arts and crafts, board games, and nature. To pass time I like playing with my dog and hanging out with friends. I recently found a deer skeleton with my family. I reassembled it, which was a new experience for me—just like reviewing this article!

AUTHORS

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Alejo Kraus-Polk is a new father and Ph.D., candidate in the geography graduate group at the University of California, Davis. Alejo's research concerns the human dimensions of landscape design and adaptation in the Sacramento-San Joaquin Delta. Alejo enjoys exploring the whole novel Bay-Delta watershed, from sea to Delta marsh to granite Sierra spires. *akrauspolk@ucdavis.edu

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frontiers FOR YOUNG MINDS

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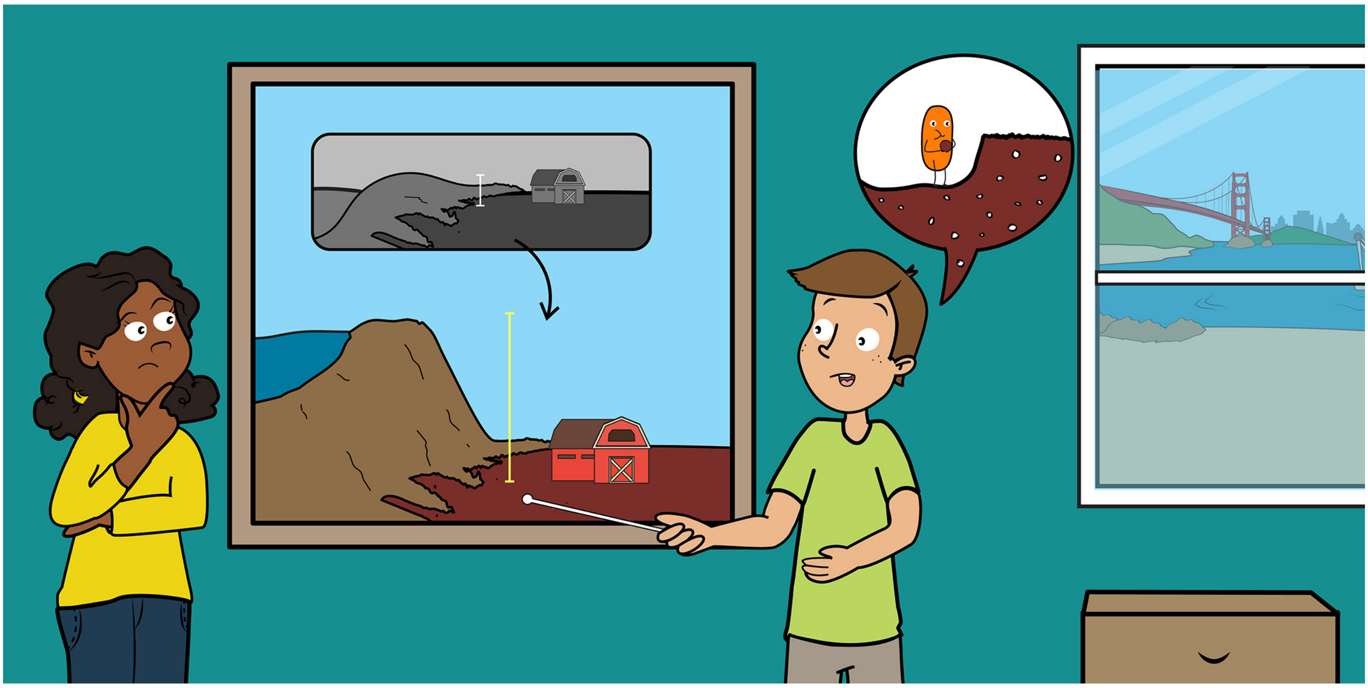

THE DANGEROUS DISAPPEARANCE OF DELTA DIRT

Dylan Stern[1], Dylan Chapple[1] and Cory Copeland[2]*

[1] Delta Science Program, Delta Stewardship Council, Sacramento, CA, United States
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YOUNG REVIEWERS:


ANDY
AGE: 14


GWEN
AGE: 13


VERONICA
AGE: 12

Across the Sacramento-San Joaquin Delta, spongy soil is sinking at a rapid rate! This issue, known as subsidence, happens in places with peat soils that have been drained. Peat soils are created over thousands of years by decaying wetland plants. Following European colonization of California, the Delta's wetlands and their peat soils were drained, and levees were built to keep the land dry. Farms now thrive on this fertile landscape. However, as drained soils are exposed to oxygen, tiny microbes rapidly consume the peat soil, which makes the land sink. Now, many Delta islands look like giant salad bowls up to 9 m deep, with fragile levees holding the rivers back. This puts communities, farms, ecosystems, and water supplies at risk from floods. The microbes in the soil release carbon dioxide into the atmosphere, which contributes to climate change. Scientists and land managers are creating new wetlands to combat subsidence in the Delta.

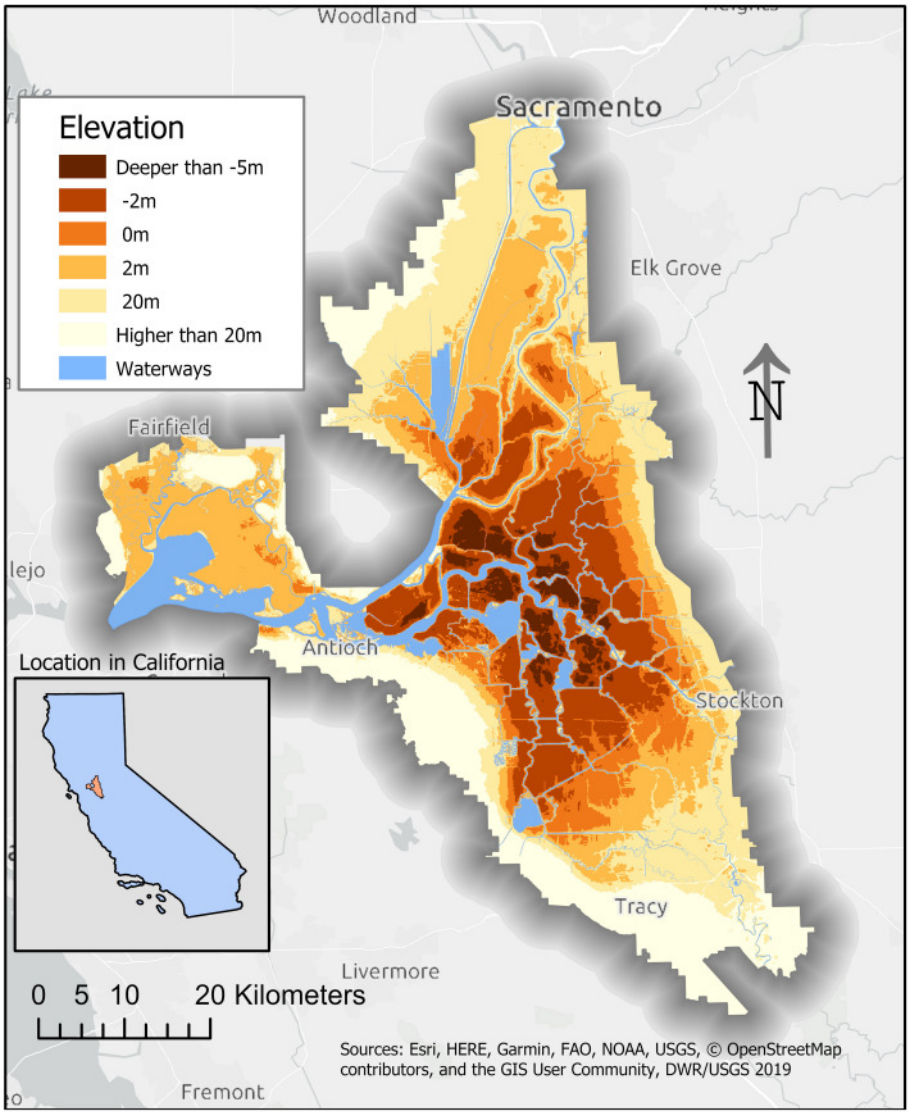

Figure 1

Figure 1

This map of elevations in the Sacramento-San Joaquin Delta shows the areas where subsidence has occurred. An elevation of 0 m indicates sea level, while negative elevations are below sea level. Notice that large areas in the central Delta have subsided to depths below sea level.

WETLAND

Also known as a marsh, land that is typically covered in water or plants that can handle flooded conditions.

PEAT

A natural brown substance in soils formed by the breakdown of dead plants and other organic material. It takes a long time to form and must be created under water.

SUBSIDENCE

The lowering of the ground level, which can be caused by microbial breakdown of organic matter, wind erosion, compaction, or groundwater pumping.

MYSTERIOUS SINKING ISLANDS

Imagine the earth beneath your feet disappearing. This may sound like something out of a horror movie, but it is happening across the world where **wetlands** have been drained. In the Sacramento-San Joaquin Delta (referred to as "the Delta"), hundreds of thousands of acres of farmland were created on former wetlands and the peat soils they created. **Peat** soils are soils formed under water by layers of decaying wetland plants. These types of soil are made of mostly organic (recently living) matter and they have lots of carbon and nutrients, making them great for farming.

However, farming on peat soil holds a hidden risk: it can cause **subsidence**. Subsidence is the disappearance of soil that results in the lowering of the ground level. In some parts of the Delta, subsidence has lowered the soil surface up to 9 m in the last 170 years [1] (Figure 1)!

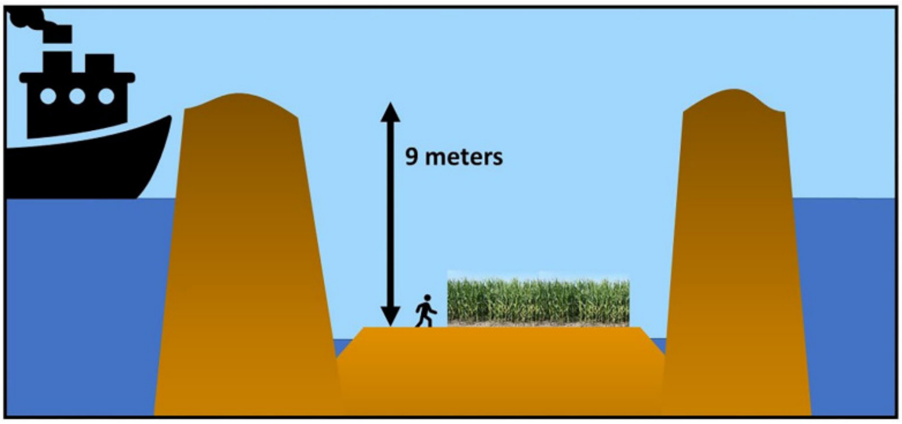

Figure 2

Figure 2

Subsidence in the Sacramento-San Joaquin Delta. Levees surround land and constantly hold water back. When water is drained from wetlands and the ground disappears due to subsidence, the levees are at greater risk of breaking, which could flood many farms and homes.

This means that if a three-story house was placed in the most deeply subsided parts of the Delta, the top of its roof would be right at the level of the water running through the nearby rivers. How could this have happened?

In the 1800's, European colonizers came to California and stole land from the area's indigenous people. The colonizers began to change that land considerably. The farms and towns that make up today's Delta were mostly wetlands that were covered with water much of the time. To farm these wet areas, people constructed **levees** (also known as dikes) to make islands and drained the wetlands. The levees kept the water out and allowed a thriving agricultural industry to develop in the area (Figure 2). Unbeknownst to these early Delta farmers, draining the Delta's wetlands had major consequences. Draining the land lets oxygen into the peat soil, which "wakes up" certain **microbes**, creatures so small you can not see them without a microscope. The microbes go to work eating the organic material and burping out carbon dioxide (Figure 3). The soil loses its structure, shrinks like a dry sponge, and is easily crushed. At first, the changes were gradual and hard to notice, but over the last century a crisis has developed. Some parts of the Delta are sinking up to 1.8 cm per year [2]! This will continue unless steps are taken now to combat subsidence.

LEVEES

Also known as a dike, a structure that prevents water from entering the land. Levees are usually long mounds of dirt that hold water back.

MICROBES

Tiny living creatures that cannot be seen by the human eye, which are responsible for many chemical and physical changes to the environment.

WHY IS SUBSIDENCE A PROBLEM?

So why is subsidence a problem in the Delta? First, hundreds of thousands of acres of farmland and many small towns in the Delta are now protected by levees. These levees are constantly holding rivers back from spilling into farms and communities, 24 h a day, 365 days per year. The more the land sinks, the greater the pressure on the levees, and the greater the risk of levees breaking and flooding people's homes and farms. Levees in the Delta have broken 87 times in the last 70 years [1]. A levee broke in 2004, flooding hundreds of acres of

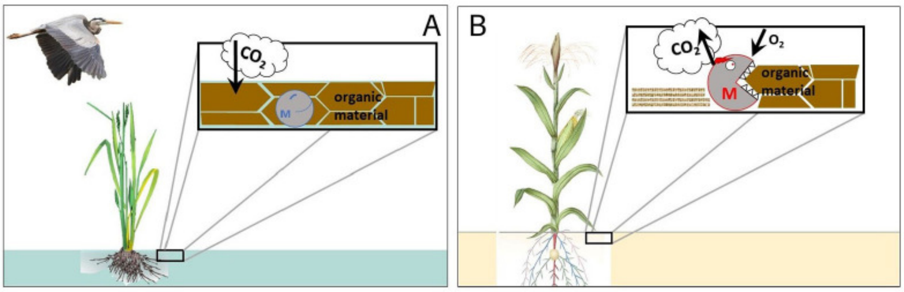

Figure 3

Figure 3

(A) In wetlands with plants like cattails or rice, the organic material (peat) is not broken down and can even build up. Maintaining water over the peat is critical because the microbes (M) that cause subsidence are not active under water. Flooded lands take up carbon from carbon dioxide (CO_2), raise the ground level, and provide habitats for wildlife such as the blue heron. **(B)** When wetlands are drained for crops like corn, oxygen (O_2) can enter the soil. This wakes up microbes (M) that devour organic material and burp out carbon dioxide (CO_2), a greenhouse gas.

farmland, and costing over $90 million USD to fix [2]! Approximately 40% of the state of California drains stormwater through the Delta so, during storms, water levels can get so high that water flows over the tops of levees. The deeper the subsidence, the harder it is to repair broken levees or to pump water out if it floods. This puts hundreds of thousands of acres of farmland, wildlife habitat, and communities at risk of catastrophic flooding. Unfortunately, this risk will only increase as climate change raises water levels and subsidence continues.

Another reason subsidence is a problem is that levees do not only protect the land they surround, they also protect one of California's most valuable resources: fresh water. The State Water Project and the Central Valley Project provide water for 2 out of 3 Californians in Los Angeles and other cities, and for millions of acres of farmland in California's Central Valley. This important water flows from large reservoirs in the mountains and must pass through Delta waterways. At times, the Delta waterways can be a little salty because they are connected to the Pacific Ocean. Saltiness increases during high tides and when freshwater flow is limited. The levees in the Delta play a critical role in keeping the water fresh: if they break, salt water will push far into the Delta. This could endanger the largest source of California's drinking water and much of the produce we enjoy.

Subsidence is also a problem because subsided lands cannot be restored to **tidal wetlands**, which are critical for the ecological health of the Delta. Tidal wetlands are ecosystems where plants grow in areas covered by water all or part of the time because they are physically connected to larger bodies of water. They also provide critical habitats for fish, birds, and other organisms, many of which are endangered and may go extinct without restoration. Over the last 170 years, over 95% of the Delta's tidal wetlands have been destroyed. Subsidence greatly limits the ability to restore most of the tidal wetlands in the region, because these wetlands can only exist if the elevation is near sea level. Many subsided areas have sunk below sea level, which means that attempts to create tidal wetlands on subsided islands would create a lake-like habitat instead.

TIDAL WETLAND

A type of wetland or marsh that is flooded and drained by tidal movement from the estuary, sea, or ocean.

The negative impacts of subsidence are not only seen in the Delta region—subsidence can also impact the entire Earth, by contributing to climate change. As peat is exposed to the air, microbes break down the peat soil by eating the organic material (Figure 3B). Like cars that run on gas, these microbes run on peat and emit carbon dioxide. This process produces huge amounts of carbon dioxide, a greenhouse gas that contributes to climate change, that escapes into the atmosphere [3]. Subsided Delta islands contribute about 2 million cubic tons of carbon to the atmosphere each year [2], or about the same amount of pollution produced by 300,000 cars.

SOLUTIONS TO SUBSIDENCE IN THE DELTA

You may find yourself asking, "Why do not we just fill up subsided areas with soil to bring them back up to safer elevations?" Unfortunately, this would require an enormous amount of soil. In fact, if you were to fill Disneyland with soil 1 foot deep, you would need to truck in about 75,000 Disneylands to bring the subsided Delta islands up to sea level [4]. There is simply no source of soil that could make this work!

So how *are* scientists and land managers working to prevent or reverse subsidence? The solutions all involve returning conditions on Delta islands closer to what they used to look like. The first step is covering the soil with water. Even a shallow pond stops the subsidence-inducing, carbon-producing microbes from eating away at the ancient peat soil. Some farmers in the Delta have started growing rice, which needs flooded soil for much of the year. Rice farming stops subsidence in its tracks while still producing food.

There is an even more powerful tool that not only stops subsidence but reverses it! What kind of amazing technology could be used to achieve this? The answer is non-tidal wetlands managed by humans. Although it is not possible to restore *tidal* wetlands on subsided islands, humans can pump water in and create vast areas of non-tidal wetlands below sea level, protected by levees. Once under water, these wetlands can create and build up peat soil, which increases their elevation [2].

It will take many years for wetlands in deeply subsided islands to reach sea level. In the meantime, human-made, non-tidal wetlands can take pressure off levees and reduce the risk of flooding with every centimeter of newly built soil they produce. Wetlands also provide habitats for wildlife like river otters, great blue herons, white pelicans, and numerous other species. Land managers have restored over 2,000 acres of non-tidal wetlands on subsided islands, and many thousands more acres of restoration are planned.

Another benefit of returning water to peat soils by creating wetlands or rice fields is that it stops the carbon dioxide emissions that contribute to climate change (Figure 3A). Land managers and scientists are working together to monitor greenhouse gas emissions from newly created non-tidal wetlands. Wetlands do not just stop the emissions; they actually *soak up* carbon dioxide in a process known as **carbon sequestration**. Even outside of California, companies and governments looking to reduce their contributions to climate change will often pay the state for carbon sequestration. So, these newly created, non-tidal wetlands not only produce new habitats, reverse subsidence, and sequester carbon, but they can also earn money.

CARBON SEQUESTRATION

Removing carbon dioxide from the atmosphere and storing it for a long time.

WE MUST THINK AHEAD!

The issue of subsidence in the Delta illustrates how people's past actions can influence current environmental conditions. If the early land conversion in the Delta had not happened, we would not need to deal with the difficulties caused by subsidence. Like many big environmental challenges such as climate change or global deforestation, the problems started before anyone alive today was even born. These environmental concerns can seem overwhelming. While we cannot change history, we can think ahead. We can use science to prevent future environmental damage and help identify solutions to current problems to benefit humans and the environment for generations to come.

ACKNOWLEDGMENTS

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YOUNG REVIEWERS

ANDY, AGE: 14

I am a 14 year old boy. My favorite hobbies are hiking, swimming, running, skiing, skateboarding, and other outdoor activities. My favorite sports are basketball, football, and baseball. In school, my favorite subjects are math and science.

GWEN, AGE: 13

Hi, my name is Gwen, I live in the U.S. and play piano and volleyball. I am in seventh grade, and my favorite subjects are science, math, art, and Spanish. I love to read, particularly Sci-Fi novels and series (I am also a huge fan of Harry Potter). I just started working with Frontiers for Young Minds, and am very excited to continue!

VERONICA, AGE: 12

I am in the 7th grade and I am very interested in science. I like to play soccer and softball. I also like to bake and sew.

AUTHORS

DYLAN STERN

Dylan Stern received a B.S., in environmental science from C.S.U. Chico in 2008, and in 2011 he received a M.S. from U.C. Santa Barbara at the Bren School of Environmental Science & Management, with a focus on water resource management. Dylan conducted field work in the Delta watershed, including Twitchell Island's carbon sequestration wetland, rice fields, and experimental wetlands. In 2015, he began working for the Delta Stewardship Council's Delta Science Program to support science funding aligned with the Delta Science Plan and the Science Action Agenda, manage contracts, and conduct independent scientific peer reviews. *Dylan.Stern@deltacouncil.ca.gov

DYLAN CHAPPLE

Dylan Chapple holds a B.A., in Environmental Studies from U.C. Santa Cruz and a Ph.D., in Environmental Science, Policy, and Management from U.C. Berkeley. His graduate research focused on tidal wetland restoration and climate in the San Francisco Bay. He has served as a CCST Science and Technology Policy Fellow in the California legislature and worked with the non-profit groups Save the Bay and Point Blue Conservation Science. He has worked at the Delta Stewardship Council as a senior environmental scientist since 2018, focusing on science support for restoration projects, adaptive management, climate change, and science coordination.

CORY COPELAND

Cory Copeland has a B.A., in geography from the Macalester College, where he studied political ecology. He attended the University of Oklahoma and U.C. Davis, where he studied water policy and landscape dynamics. He currently works as a senior environmental scientist at the Delta Stewardship Council, where he models landscape change due to subsidence and flood risk resulting from climate change (viewperformance.deltacouncil.ca.gov).

BIODIVERSITY
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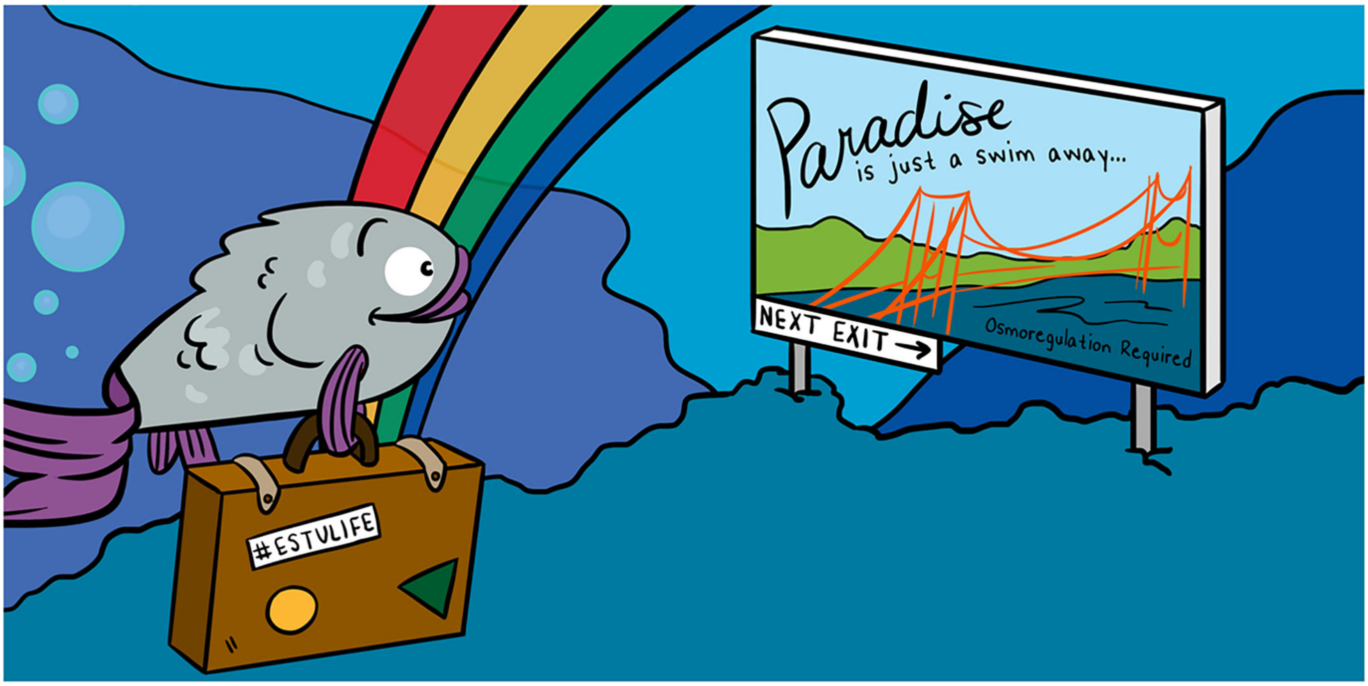

ESTUARIES, A HAPPY PLACE FOR FISH

***Pedro Morais*[1*] *and Ester Dias*[2]**

[1] *CCMAR–Centre of Marine Sciences, University of Algarve, Faro, Portugal*

[2] *CIIMAR–Interdisciplinary Centre of Marine and Environmental Research, University of Porto, Porto, Portugal*

YOUNG REVIEWER:

FRESIA

AGE: 11

Anchovies, salmon, sardines, gobies, mullets, flounder, bass, barbels, eels, shad, and even sharks—what do they have in common? Well, at certain points in their lives you may find them in estuaries, the final sections of rivers before they meet the ocean. Some fish live in estuaries their entire lives. However, some fish species prefer living in the freshwater parts of estuaries, others only live close to the ocean, and a few others spread throughout the estuary. Some species prefer living close to the bottom, some in marshes, and some constantly swim around in the estuary. Some prefer eating other fish, while other species like worms, or insects, or microscopic animals. Unfortunately, many estuarine species are in danger, and all because of humans. In this article, we will tell you why estuaries are such special places for fish and describe some of the species that call the San Francisco Estuary their home.

FISH SUPERPOWERS

Have you noticed that fish can be found almost everywhere that you can find water? There are fish living in the deepest part of the ocean, the Mariana Trench in the Pacific Ocean, at 10,994 m deep. Fish living there, like the Mariana snailfish, have the superpower of resisting the freezing temperature and crushing pressure of 11 km of water on top of them. They also live their lives in total darkness [1].

In the African savannah, you can find the incredible turquoise killifish living in small, shallow pools that form when it rains. Rainwater awakens the eggs that were kept protected in the soil since the previous rainy season. Once awake, the eggs hatch. Their superpower allows the turquoise killifish to hatch from their eggs *only* when the environmental conditions are perfect [2].

OSMOREGULATION

The ability to regulate and maintain the right amount of water, nutrients, and salts inside cells.

Fish also have a superpower called **osmoregulation** [3]. Like humans, fish need to keep the right amount of water, salts, and nutrients in their cells. Without this superpower, fish living in the ocean would lose water from their cells and die, because the ocean has much more salt than fish tissues do. Fish living in rivers, called freshwater fish, have the opposite problem. Without osmoregulation, too much water would enter their cells and cause the cells to burst. Usually, fish that live in freshwater cannot use osmoregulation in the ocean, and the other way around. Yet, a few fish species can live in ecosystems where the salinity—the amount of salt in the water—is constantly changing. This is what happens in estuaries. Here, fish species push their osmoregulation superpower to the limit!

TIDES STIR THE SALT IN ESTUARIES

TIDES

Tides exist because the moon acts as a magnet causing the rise and fall movement of water in estuaries, coastal lagoons, and along the ocean shores.

HIGH TIDE/LOW TIDE

The high tide occurs when one side of the Earth is the closest or furthest away from the moon. The low tide occurs when that side of the planet is in between those points.

Estuaries are the final sections of rivers before they meet the ocean. Here, the water is brackish, which means that it is not as salty as the ocean, nor as fresh as in rivers. Salinity varies a lot in estuaries because **tides** mix the water from rivers with water from the ocean [4]. In most estuaries, the water is saltier as you get closer to the ocean. During **low tide**, salinity is at its minimum in the estuary because the water coming from rivers pushes estuary water out to the ocean. During **high tide**, salinity is at its maximum because salty ocean water enters the estuary (Figure 1). Salinity in estuaries may also vary a lot due to weather. If it rains or snows a lot in one season or during a certain year, the estuary will become less salty than usual. But if it does not rain or snow as much as normal, the estuary will become saltier.

Fish living in estuaries must adapt to the constant changes in salinity. Living in estuaries is difficult for fish! Only those species that push their osmoregulation superpower to the limit can live in estuaries. Yet, for these fish, estuaries are a happy place to live [5]!

ESTUARIES: NURSERIES FOR FISH

Most estuaries around the world are unhealthy because they are surrounded by cities, factories, and harbors. Worldwide, 2.4

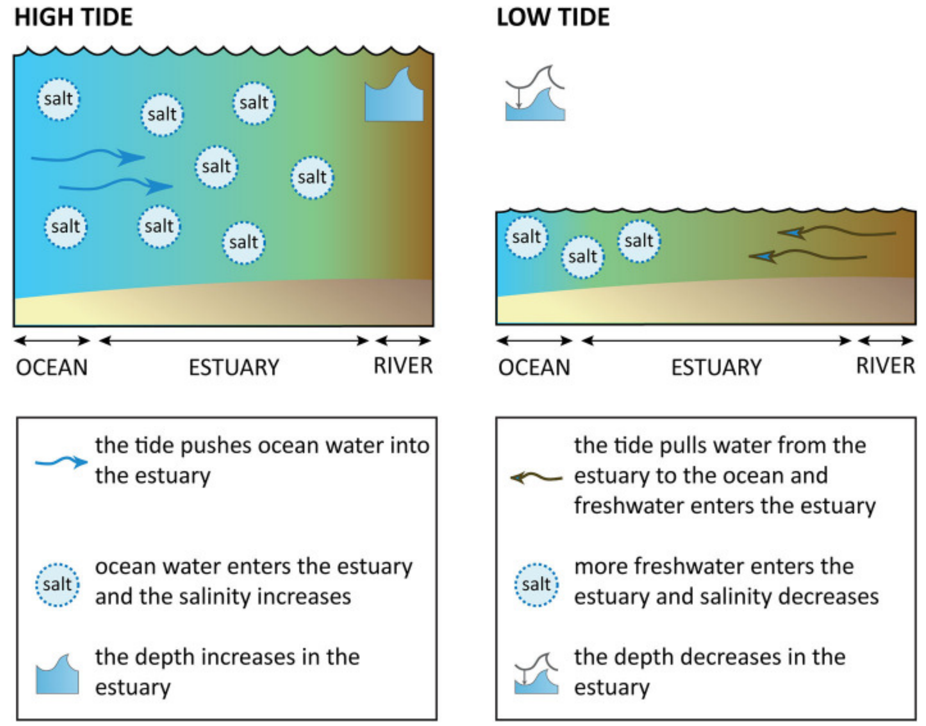

Figure 1

Figure 1

Estuaries during high tide and low tide. During high tide, ocean water enters the estuary, increasing the salinity and water depth. During low tide, the ocean retreats and fresh water from rivers is pulled downstream, decreasing salinity and water depth (Image credit: IAN Symbol Libraries; https://ian.umces.edu/symbols).

billion people live within 100 km of the ocean, very close to estuaries. However, healthy estuaries can be wonderful places for fish to live.

Estuaries are the perfect **nursery** for many fish species [6]. Estuaries allow young fish to grow strong and healthy because food is abundant and diverse. The greenish or brownish color of the water makes it difficult for predators to see young fish. In an estuary's streams and **marshes**, young fish can also find excellent hideouts from big predators and refuge from strong currents.

NURSERY

Ecosystem that provides increased protection and food for the development of most young fish in a population.

MARSH

Shallow aquatic habitat that surrounds estuaries and coastal lagoons. It has vegetation that is adapted to salty water. In tropical regions, mangroves are the equivalent habitat to marshes.

Conditions in estuaries can be so good that fish migrate from the ocean into the estuaries and nearby rivers to reproduce, like the Pacific lamprey in the San Francisco Estuary. Then, larvae and juveniles will grow up there before migrating to the ocean [7]. This species belongs to a group of **migratory fish** called anadromous fish [7]. Other migratory fish have a different strategy, like the American eel. This species migrates to estuaries when they are larvae or juveniles because they can grow faster and stronger than they could in the ocean [7]. They migrate back to the ocean once it is time to reproduce. The American eel was introduced into the San Francisco Estuary but failed to establish a population. This species belongs to a group of migratory fish called catadromous fish.

MIGRATORY FISH

Fishes that need to move between different habitats during specific phases of their life to reproduce, feed, grow, and/or find refuge from predators.

Other species even live their entire lives in estuaries, so they are called estuarine residents. This is the case of the tule perch in the San

Figure 2

Figure 2

Examples of fish species that live in the San Francisco Estuary and adjacent ecosystems. The American eel is an exception because, after being introduced, it failed to establish a population in the Estuary (Photo credits: BioDiversity4All.org).

Francisco Estuary [8]. Other species may *sometimes* use estuaries as nurseries, like the leopard shark [9]. This species is called estuarine facultative [5]. Pictures of various fish species that live in the San Francisco Estuary can be seen in Figure 2.

WHY DO FISH AVOID THEIR NEIGHBORS?

Although it seems there is plenty of space and food in estuaries, along with secret hideouts where fish can hide from predators, each species avoids eating the same kinds of food as other species, and species also avoid living in the same place at the same time [5]. These behaviors are a brilliant strategy to decrease competition, particularly when food or space becomes scarce.

ECOLOGICAL NICHE

Conditions that exist in an ecosystem that allow a species to live. Usually, temperature, salinity, depth, or food preferences are used to describe the ecological niche of fish.

Scientists can determine how much competition exists between species by studying their **ecological niche**, which is the fancy expression for the types of conditions that a species likes [10]. The ecological niche of a fish includes the water temperature, salinity, or types of sediment it prefers, like sand or mud. The ecological niche may also include the food a species likes. In the San Francisco Estuary, you can find fish that always live in the rivers or the upper part of the Estuary where the water is not salty, such as the Sacramento blackfish. There are also fish that can live either in freshwater or in the brackish part of the Estuary, like the prickly sculpin. Other species only live in the brackish part of the Estuary, like the cabezon. So, you can deduce that Sacramento blackfish and cabezon will never compete for food or space because they never live in the same place. This means that their ecological niche is completely different.

But when species *do* live in the same place, their ecological niche may overlap. However, fish can still avoid competition. They might eat different foods or live at different depths. For example, there are benthic species that lay on the bottom most of their lives, pelagic species that are always swimming, and demersal species that live in both places. So, let us examine three species—Northern anchovy, starry flounder, and white croaker—that live in the brackish part of the San Francisco Estuary to see how much competition exists between them (Figure 3). The starry flounder is a benthic species as juveniles and adults, that eats worms, small crabs, and small clams. The Northern anchovy is a pelagic species that only eats **zooplankton**. So, the competition between starry flounder and Northern anchovy is very low. On the other hand, the white croaker is a demersal species. It spends time swimming around and going down to the bottom to eat clams, crabs, shrimp, or worms. So, the ecological niche of the white croaker and Northern anchovy do not overlap much because they spend only a little time in similar places. However, the competition between starry flounder and white croaker is greater because they like eating similar things that live near the bottom.

ZOOPLANKTON

Tiny animals that live in the water. Some resemble miniature shrimp, crabs, or snails, and you need a magnifying lens to see them properly.

PROTECTING FISH IN ESTUARIES AND ELSEWHERE

Fish living in the San Francisco Estuary have seen better days [11]. Some species are in danger of extinction. This is the case of the delta smelt, which live their entire lives in the Estuary and other nearby

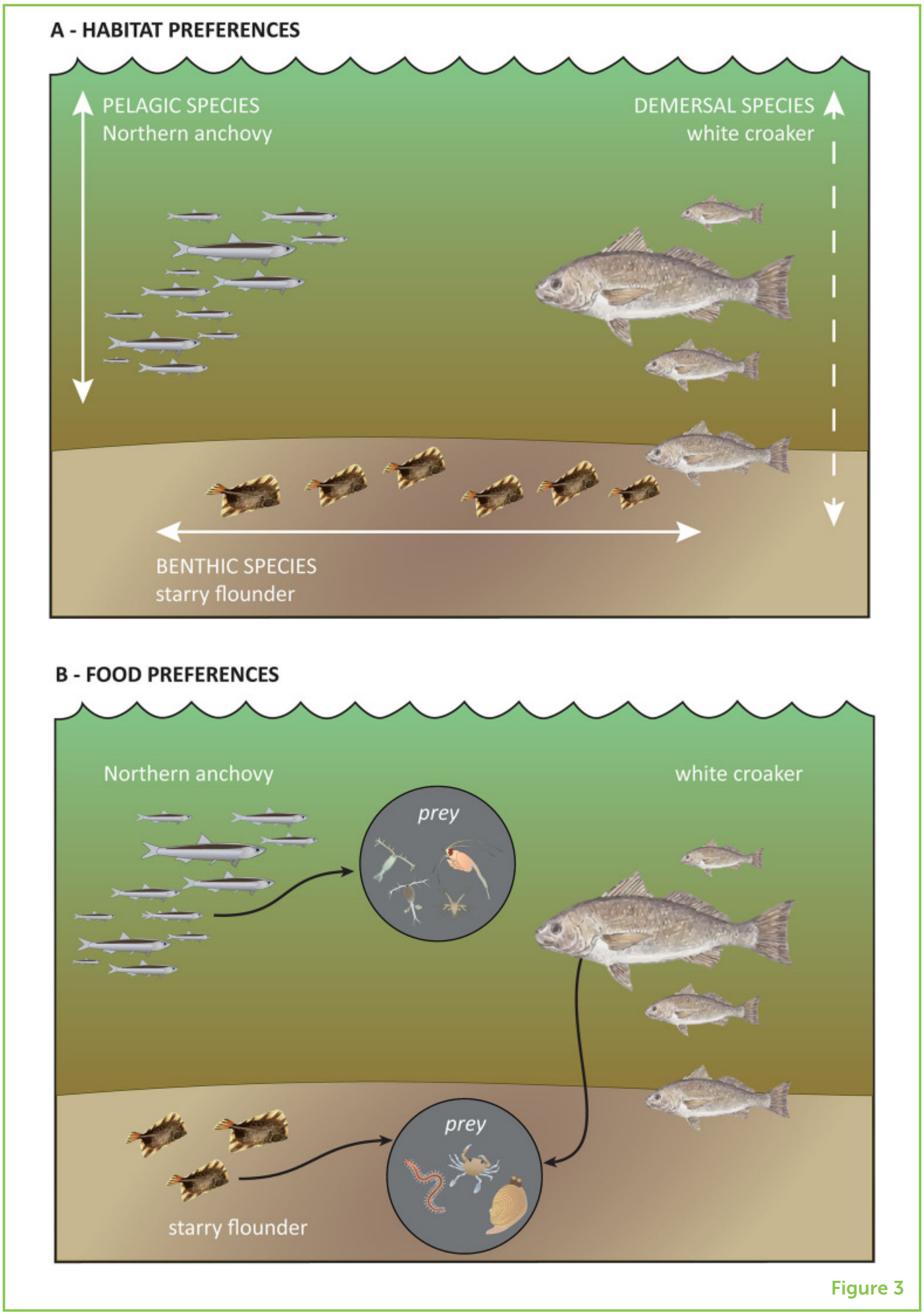

Figure 3

Ecological niche overlap between three fish species that live in the San Francisco Estuary. Here, we determined competition between fish species by analyzing **(A)** habitat preference and **(B)** food preference. Competition between starry flounder and Northern anchovy is low because they live in different areas and do not eat the same foods. There is only a little competition between Northern anchovy and white croaker, because they share space but not prey. The competition between white croaker and starry flounder can be greater because they eat the same prey (Image credit: IAN Symbol Libraries; https://ian.umces.edu/symbols).

ecosystems, or of the winter-run Chinook salmon, which only spend a few weeks in the Estuary at the most. These species are in danger from water pollution, overfishing, invasive species, destruction of marshes and shorelines, dams, and climate change—the same reasons that many fish species all over the world are in danger.

Protecting fish and other wildlife may seem, at times, a lost cause. But people are becoming more mindful of the environment. More and more people avoid wasting good water in their homes. Others work to establish agricultural practices that do not use pesticides or fertilizers that can harm the environment. Other people choose to use clean, renewable energy in their homes, and some deliver dangerous chemicals to recycling centers instead of pouring them down the drain.

If you want to protect fish and other wildlife, you can start by sharing this article with your family, friends, and teachers. Make a list of your ideas about how to protect the animals and plants from your region. Find people with the same goals. Write or talk with the mayor of your city or village. Let everyone know that a healthy environment is important for all living creatures on the planet and that we need to protect them before it is too late.

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YOUNG REVIEWER

FRESIA, AGE: 11

I love science and math, but I am not a fan of history and geography. My big passion is animals. I have a snake named Sacha jr. and a rabbit named Luna, and I love to raise silkworms and search for lizards and other animals in the wild. I am also learning to ride horses and I love using creativity to make crafts.

AUTHORS

PEDRO MORAIS

My passion for marine biology began when I was 7 years old. I went on vacation with my parents and sister to a lovely beach in southern Portugal. There, I spent all the time I could in the tide pools searching for fishes, crabs, shrimps, and anemones. I have studied all kinds of aquatic organisms (bacteria, microscopic algae, jellyfish, clams, crabs, birds, fish, and even whales and dolphins) from the deep ocean to shallow lagoons, estuaries, rivers, lakes, and streams. During my free time, I enjoy dancing tango, taking photographs, woodworking, fixing and restoring old things, and researching my ancestry. *pmorais@ualg.pt

ESTER DIAS

I am a researcher at the Estuarine Ecology and Biological Invasions research group (CIIMAR-University of Porto, Portugal). As a child, I was curious about how animals behave, what they eat, and why they need to migrate long distances to reproduce. So, becoming a biologist was my chance to find the answer to these questions. So far, I have studied small aquatic animals called zooplankton (some only 1 mm in size), clams, aquatic birds, fish, and even marine mammals. Currently, I study the migrations of fish, the impacts of biological invasions, and what is on the menu of each aquatic species.

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KEEPING AN EYE ON WATER QUALITY FROM THE SKY

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YOUNG REVIEWER:

AVIV
AGE: 9

You can learn a lot about rivers, lakes, estuaries, and oceans by looking down at them from the sky. Scientists use a technique called remote sensing to measure the amount of light or heat energy reflected and emitted from the Earth. Sensors can be on satellites or mounted on airplanes, helicopters, or drones. Scientists use this information to map the quality of water in the San Francisco Bay-Delta estuary. Remote sensing helps scientists see where and when there might be problems for human health or for the plants and animals living in the estuary.

WHAT IS WATER QUALITY AND WHY IS IT IMPORTANT?

Water quality is important for humans and the environment. Water quality tells us how good or bad water is for swimming in or for drinking. Farmers need clean water to grow food and raise farm animals. Wildlife and fish also need good water quality [1, 2].

WATER QUALITY
A measure of the condition of water and how clean it is for plants and animals, including humans.

Poor water quality is often caused by pollution and can create health risks for humans, plants, and animals. Monitoring water quality helps

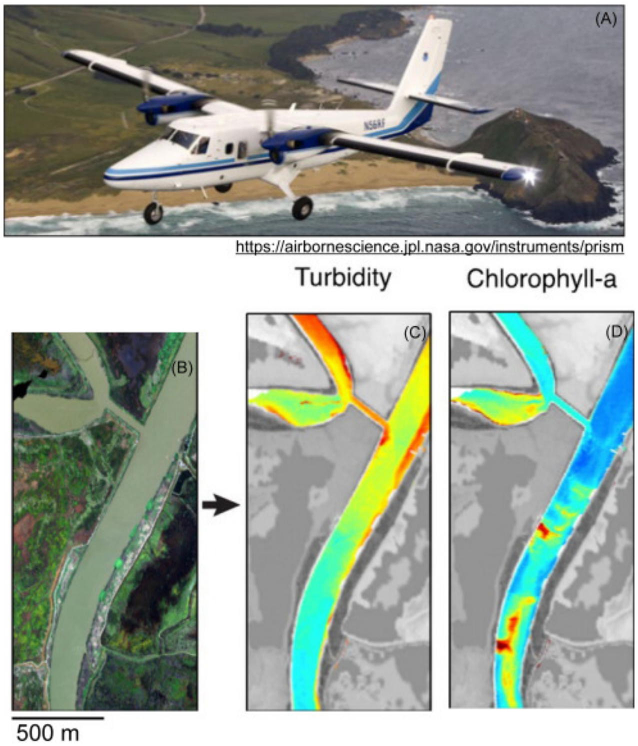

Figure 1

Figure 1

(A) Remote sensing imagery of turbidity and chlorophyll-a was measured using an airplane. **(B)** The imaged area is shown in a normal photo. **(C)** Turbidity is shown, with red as the most turbid and blue the least. **(D)** Chlorophyll-a concentrations are shown, with red as the most concentrated and blue the least (Image credit: [3]). Image has been modified after [3].

identify sources of pollution. Scientists can monitor water quality using sensors in the water. They also can monitor water quality remotely, from up in the sky. Scientists call this kind of monitoring **remote sensing** because it can be conducted without touching the water. Using satellites, airplanes, helicopters, and drones, scientists can have a bird's–eye view of an entire **estuary**. This way, they can collect data in much less time than they could in a boat or from shore.

Chlorophyll-a is a pigment found in plants and microscopic algae. Chlorophyll-a is an important indicator of water quality because it is a measure of algae growing in a waterbody. When algal concentrations are too high, they can lower the amount of oxygen dissolved in the water, and they can make animals and people sick. For example, chlorophyll-a makes microscopic algae—and the water they live in—appear green. The greenness of the water helps scientists see where and when these algae grow. Scientists use the term **algal bloom** to describe areas where microscopic algae are growing fast and covering large areas. Some algal blooms are poisonous. Scientists can measure how green the water is from the air, using remote sensing cameras designed to detect the various colors of sunlight reflected by the water [3]. Remote sensing makes it possible to map greener waters in the estuary where there are algal blooms. Maps of algal blooms show scientists where and when to monitor for microscopic algae directly from a boat or from shore. This information helps people and their pets avoid areas that could make them sick.

REMOTE SENSING

Gathering information about the environment at a distance, for example from an aircraft or satellite.

ESTUARY

Area at the end of a river where freshwater from the river mixes with saltwater from the ocean, creating water that we call brackish.

CHLOROPHYLL-A

A green pigment in plants and certain algae that captures the energy of the sun for photosynthesis.

ALGAL BLOOM

Rapid increase in the algae population in any body of water (river, lake, estuary, or ocean).

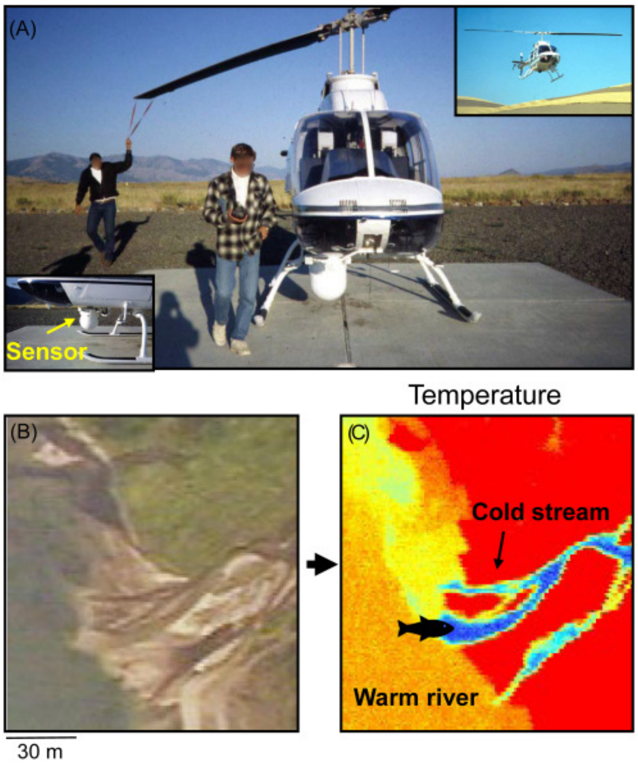

Figure 2

Figure 2

(A) Thermal infrared images were obtained with sensors mounted on a helicopter. **(B)** The imaged area is shown in a normal photo. **(C)** Temperature is shown from coldest (blue) to warmest (red). Note the cold stream entering the warm river. Coldwater fishes live primarily in the colder areas.

HOW DOES REMOTE SENSING WORK?

Remote sensors are like cameras that can "see" water quality by detecting energy coming from the water's surface. These sensors are mounted on satellites and a variety of aircraft (Figures 1, 2), each with their own pros and cons. Airplanes and helicopters can be flown at almost any time but monitoring trips are expensive and require a lot of planning. Drones take high-quality images and are inexpensive to fly, but their battery life is short. After 10–15 min, they must land to replace or recharge batteries. An advantage of remote sensing with satellites is that satellite images can cover large areas of the Earth, and the images are often free to download, but satellites only follow a specific orbit around the planet, which makes it impossible to choose the location and timing of monitoring.

Water quality indicators like chlorophyll-a reflect and emit energy from the water's surface. Remote sensing cameras detect this energy and use it to create an image like a photo. Like a camera, the human eye is a kind of remote sensor that sees sunlight reflected off the water in various hues of red, green, or blue. For example, chlorophyll-a in microscopic algal blooms reflects more green light than other colors. Muddy water has high **turbidity** and reflects more red and green light, making the water look brownish [3]. Heat is another kind of energy that comes from the water's surface, but we cannot see heat with our eyes.

TURBIDITY

A measure of how cloudy, or muddy, the water is, usually caused by floating particles that are too small to be seen without magnification.

THERMAL INFRARED CAMERA

A non-contact device that detects infrared energy (heat) and converts it into a visual image.

GROUND-TRUTHING

Process of comparing the data from an image obtained from remote sensing to data obtained on the ground or in the water.

Some snakes, like vipers, pythons, and boas, use special pit organs located between the eyes and nostrils to detect heat energy from a meter away [4]! The pit organ is used for finding prey. Remote sensing with a **thermal infrared camera** is like using rattlesnake vision to map water temperature, to see where water is too warm for fish and other aquatic organisms (Figure 2) [5].

Mapping and monitoring water quality from the sky is difficult. Scientists use a process called **ground-truthing** to make sure that measurements from the sky match measurements collected by scientists on the ground or in the water. Images from the sky may not be clear when it is too cloudy or smoky from wildfires. Also, because satellite images are taken from so far away in space, they are not very detailed. Aircraft and drones fly closer to the ground and may not cover large areas like satellites, but they provide very detailed images of small areas (Figures 1, 2).

HOW IS REMOTE SENSING USED IN THE SAN FRANCISCO BAY-DELTA?

Scientists in the San Francisco Bay-Delta estuary (California, USA) used remote sensing to measure turbidity and algal blooms in the water [3]. They investigated how these water-quality indicators interacted. The maps of turbidity and chlorophyll-a were very detailed and allowed researchers to identify sources of pollution. They also helped scientists and managers understand how wind, dry conditions, and floods can affect turbidity patterns that influence where fish live. Remote sensing of water temperature could also be used in the estuary to understand which areas are too warm for fish to live in [5].

WHY USE REMOTE SENSING IN THE SAN FRANCISCO BAY-DELTA ESTUARY?

The San Francisco Bay-Delta estuary is 200 km long and covers about 4,000 km^2. Sampling water quality by boat over such a large area is difficult, expensive, and time-consuming. It requires many people, boats, and lots of equipment. Because of this, most water-quality sampling occurs only once a month or even less. Using remote sensing, scientists can map and monitor many more locations in a short period of time. Remote sensing imagery can be combined with other data on weather and water flow to understand and conserve the estuary. Future technological advances will expand the capability of remote sensing and automated sensors to better complement data collected at monitoring stations and during boat surveys.

In summary, scientists learn a lot about the quality of the water in the San Francisco Bay-Delta estuary using remote sensing. This research is important because it helps scientists see where and when there might be problems for human health or for the plants and animals living in the estuary.

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YOUNG REVIEWER

AVIV, AGE: 9
A huge Harry Potter fan! I love reading books! I spend many hours reading on my Kindle, especially Harry Potter—I have read the entire series 20 times! I also love jamming on my electric piano, jump-roping, and skipping when I am happy. I like eating salads and home cooked meals, but I also have a big sweet tooth—chocolate is yummy! As a vegetarian, I love nature—learning about it, protecting it, and enjoying it!

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Francine Mejia is a biologist in the U.S. Geological Survey, Forest and Rangeland Ecosystem Science Center, Cascadia Field Station in Seattle, WA, USA. Since Francine was a little girl, she has been interested in the environment and all wild animals. She currently studies water temperature and the aquatic organisms that live in the rivers, streams, lakes, and reservoirs of northern Idaho. She also loves dogs and cats. *fmejia@usgs.gov

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CÉDRIC G. FICHOT

Cédric Fichot is an assistant professor in the Department of Earth and Environment at Boston University, in Boston, MA, USA. He has always loved outer space and the underwater world. As a kid, he spent many of his summers snorkeling in Corsica and exploring what is below the water surface. Cédric now uses remote sensing to study aquatic environments. He loves to go hiking and to spend time outside with his wife and their three children.

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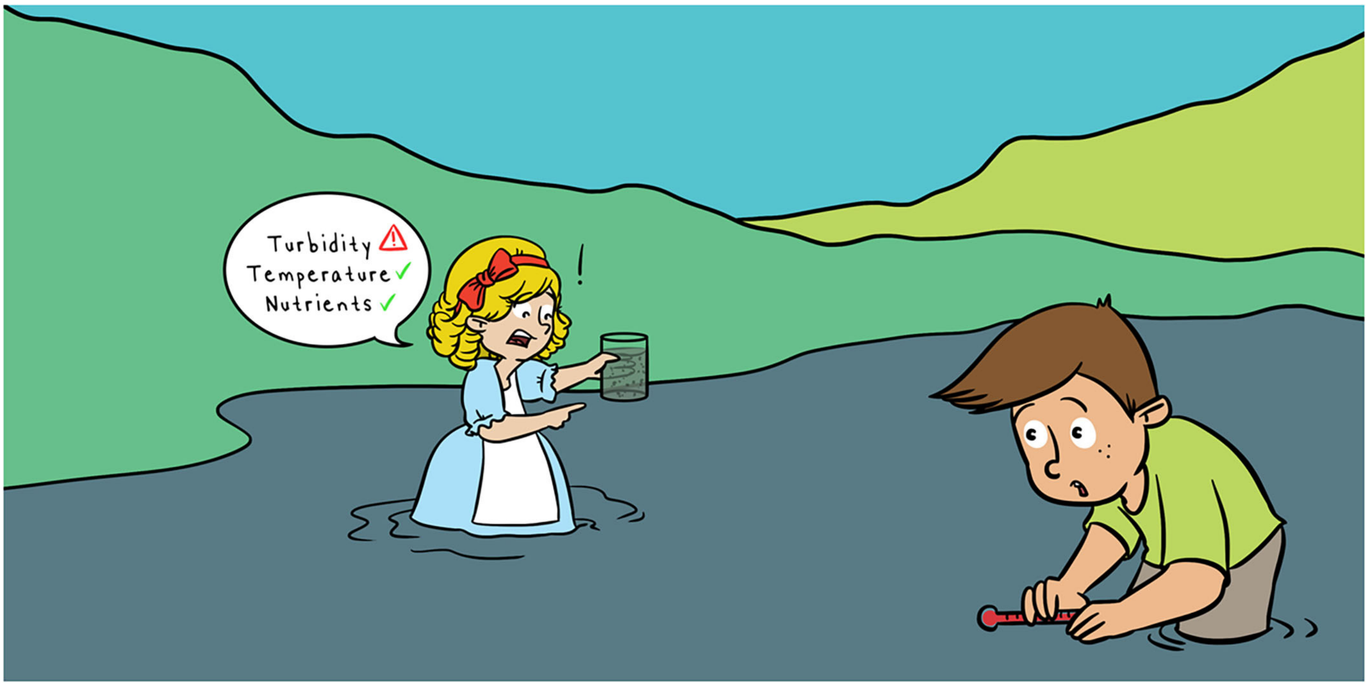

GOLDILOCKS AND THE SAN FRANCISCO ESTUARY: HOW SCIENTISTS DETERMINE WHEN WATER IS "JUST RIGHT"

Morgan N. Martinez and Theodore M. Flynn**

Division of Integrated Science and Engineering, California Department of Water Resources, West Sacramento, CA, United States

YOUNG REVIEWERS:

DAVID
AGE: 10

VARDHAN SINGHAL
AGE: 10

Have you ever accidentally gotten seawater in your mouth? You probably spit it out because it tasted so bad, right? Even though it looks clear, water in rivers, bays, and oceans contains lots of other things besides H_2O, including some things that are not healthy for people or animals! To determine the quality of a body of water, scientists measure the temperature and how much salt, sediment, and nutrients are present in that water. Too much or too little of these things, caused by pollution, floods, or droughts, might be bad for the health of the environment. Just like the porridge in the story of Goldilocks and the Three Bears, water quality must be "just right" to be healthy for the living things that need it.

WHAT MAKES WATER "JUST RIGHT"

There is much more to water than what meets the eye. While it may look clear to us, there are many things found in water that we cannot

WATER QUALITY

A measure of how suitable a body of water is for a specific use.

TURBIDITY

A measure of how cloudy the water is, usually caused by floating particles.

ESTUARY

A water passage where the salt water from the ocean meets the freshwater from a river.

see, such as salt, sediment, oxygen, and nutrients. All these things together characterize how healthy or unhealthy the water is. Scientists call the health of the water **water quality**. Estuaries are important ecosystems where freshwater from high up in the mountains meets the salty water from the ocean. The water in estuaries is critically important for people, plants, and animals because it provides a place to live, the relief of a cool drink, and tasty food to eat. Unlike lakes or ponds, water in estuaries is in constant motion, sloshing back and forth due to tides, gravity, and rain. As a result, the water quality is always changing too. Scientists who study estuaries must therefore constantly monitor the water quality to make sure it is healthy for the creatures that live there.

How do we know if water quality is healthy or unhealthy? In the story of Goldilocks and the Three Bears, a little girl named Goldilocks explores the house of the three bears while they are away. After trying out each bear's furniture and food, Goldilocks discovers that she does not like porridge that is scalding hot or ice cold, or beds that are rock hard or pillow soft. Instead, she prefers things between these two extremes, where it is "juuuuust right." Like Goldilocks, all living things need balance in their environments to thrive. In the remainder of this article, we will explain three components of water quality that are often closely monitored by scientists: **turbidity**, temperature, and nutrients.

TURBIDITY

Let us look more closely at one component of water quality, called turbidity. Turbidity is a measure of how cloudy the water is. High turbidity can occur when a lot of water is flowing through the **estuary**,

Figure 1

Figure 1

The delta smelt, an endangered fish, native to the San Francisco Estuary, that is impacted by changes in water quality.

Figure 2

A research boat navigating the waterways of the San Francisco Estuary.

disturbing the sediment on the bottom, and scattering it throughout the water. This makes the water appear cloudy. On the other hand, low turbidity occurs when there is not a lot of sediment or other material floating through the water column, and you can usually see straight to the bottom because it is so clear. But which is better for fish and other creatures living in an estuary: low turbidity or high turbidity?

The answer is a bit complicated, but it helps to think about it from the point of view of the fish. Let us consider a very important fish friend, the delta smelt (Figure 1). This small, transparent fish is native to California's San Francisco Estuary (Figure 2). Scientists have discovered that turbid (cloudy) water is a critical feature of its habitat [1]. This is probably because delta smelt are small, so turbid water helps them hide from big predators that want to eat them. For a predator fish like the striped bass, however, turbid water makes finding things to eat (like the delta smelt) more difficult. From the perspective of the smelt, high turbidity is helpful. On the contrary, high turbidity might be detrimental to the survival of the striped bass. Just like the three bears preferred different porridges and beds (food and habitat) various animals in the estuary prefer different types of conditions. Managing an ecosystem as complex as an estuary requires scientists to balance many competing needs.

TEMPERATURE

Anyone who has ever taken a relaxing shower or bath knows that warm water can feel great. For people, a warm bath can be the perfect way to relax after a stressful day. While soaking in warm water may make us calm and happy, for some fish in estuaries it is just the opposite: warm water stresses them out! Small, natural changes in water temperature are being made worse by global processes like climate change, and this is putting fish like the delta smelt in jeopardy. In the past 10 years, we have experienced many of the hottest years on record. These scorching temperatures do not just make those of us on land sweat and look for relief in the shade, they change the behavior of fish too!

Warmer water causes some species of fish to change habitats, to find cooler places to live. A recent study found that just a few degrees change in temperature, from 17 to 21°C, was enough to change how delta smelt swim and makes them easier for predators to catch and eat [2]. Warmer water can also increase the risk that fish like salmon will get certain diseases. To help keep water temperatures in the San Francisco Estuary cool in the sweltering summer weather, scientists and officials often release colder water from behind dams, to keep the rivers at a safe temperature for fish.

NUTRIENTS

If you have ever looked at the back of a vitamin bottle, you know that we need to eat many different nutrients to stay healthy! Animals and plants also need a balanced diet with plenty of nutrients. For creatures that live in the water, two of the most important nutrients are nitrogen (N) and phosphorus (P). Keeping these nutrients in balance is extremely important. Where do the nutrients in the water come from? In places like the San Francisco Estuary, nutrients in the water mainly come from human activities! When fertilizer (which contains lots of nutrients like N and P) is applied to lawns or to crops on a farm, not all of it is used by the grass or plants. When it rains, some of those nutrients wash away and enter the water system, eventually ending up in rivers, estuaries, and bays. **Wastewater**, which enters the water system via sewers, is also high in N and P.

The proper amount of nutrients in the water is important to help plants (and the animals who eat those plants) to grow, but there can be too much of a good thing! An excess of nutrients in the water can cause some very tiny plants, called **phytoplankton**, to quickly grow to high numbers. This is called an **algal bloom** [3]. While phytoplankton are a very important part of an estuary's food web, a dense bloom of phytoplankton can be harmful, because some produce toxic chemicals called **microcystins**, which make the water unsafe for drinking or swimming (Figure 3)[1]. Making things even worse, when the nutrients in the water are used up, the phytoplankton die and are consumed by bacteria that deplete the oxygen in the water, resulting in a condition called **hypoxia**. Fish need to breathe oxygen with their gills, so when water becomes hypoxic, large numbers of fish can die. Unfortunately, the warming water temperatures caused by climate change often make harmful algal blooms worse.

WASTEWATER

Water that has been used and contaminated by humans and must be treated and cleaned before it can be returned safely to the environment.

PHYTOPLANKTON

Very small organisms that create food from sunlight using photosynthesis. These organisms are an important part of the food web in estuaries and many other environments.

ALGAL BLOOM

Quickly growing microscopic algae that often results in colorful scum on the surface of the water.

MICROCYSTIN

A toxic chemical created by very small organisms called phytoplankton. Microcystin is harmful to fish, people, and other creatures.

[1] See The Frontiers for Young Minds article "Are You a HAB Warrior?" for more information: https://kids.frontiersin.org/articles/10.3389/frym.2021.611282.

HYPOXIA

A condition that occurs when the amount of oxygen dissolved in water becomes too low for fish to breathe through their gills. Hypoxia often happens because of pollution.

Figure 3

A harmful algal bloom caused by overgrowth of *Microcystis* algae in the San Francisco Estuary.

Figure 3

HEALTHY WATER, HEALTHY ORGANISMS

As you can see, water quality is made up of many different components. Most creatures (including people) need those components to be in balance so that they can stay healthy. Managing that balance can be challenging for scientists. As we have learned, it *is* possible to have too much of a good thing. While turbidity, temperature, and nutrients all have an impact on water quality, extremes of any of these factors, whether too much or too little, can be detrimental to the creatures that live in aquatic ecosystems. So, the next time you take a trip to a river, lake, or even the ocean, take a closer look at the water and remember that everything that makes the water "just right" is just beyond what your eyes can see.

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YOUNG REVIEWERS

DAVID, AGE: 10
I am David and I like to carve things and build. I like constructing furniture and I like to write letters. I am 10 and I am in grade 5.

VARDHAN SINGHAL, AGE: 10
My name is Vardhan and I am 10 years old. I enjoy cricket and reading books on outer space. My favorite subjects are Math and English.

AUTHORS

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I am an environmental scientist for California's Department of Water Resources in the Division of Environmental Services. I received my degree in biological sciences with a concentration in ecology, evolution, and conservation from California State University, Sacramento. My work is focused on monitoring the water quality and aquatic organisms that live in the San Francisco Estuary and I have spent many field days navigating through these waters aboard a 60-foot research vessel. *morgan.martinez@water.ca.gov

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ARE YOU A HAB WARRIOR?

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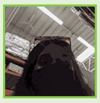
YOUNG REVIEWERS:


MEHA
AGE: 15


NIVEDITA
AGE: 14


SHREEYA
AGE: 11


SHRIYA
AGE: 13

Microalgae and cyanobacteria are tiny, microscopic plant-like organisms that float in the water and grow using nutrients from the water, energy from the sun and carbon dioxide gas from the air. Most microalgae and cyanobacteria are helpful because, like grass for cows on land, they provide food for aquatic animals. However, some microalgae and cyanobacteria are poisonous and when large numbers of them occur, they are called harmful algal blooms, or HABs for short. HABs can poison both humans and animals through the food they eat, the water they drink, and even the air they breathe. HABs are increasing within lakes, rivers, oceans, and estuaries worldwide because of pollution and climate change. This article will tell you about HABs in San Francisco Estuary, USA: who they are, what they look like, why they occur, how they affect plants, animals and people, and things you can do as a HAB warrior to stay safe and prevent their spread.

WHAT ARE HABS?

Harmful algal blooms, or HABs for short, are poisonous microscopic and floating plant-like organisms composed of **microalgae** and **cyanobacteria** that may cover broad areas of rivers, lakes, **estuaries**, or oceans. Most coastal areas of the world experience marine HABs each year. The HABs that form these blooms are so small (less than the diameter of a strand of hair) that we need a high-powered microscope to see them clearly. Microalgae and cyanobacteria convert light energy from the sun, nutrients from the water and carbon dioxide gas from the air into the sugars that they need to grow, through a process called photosynthesis[1]. This process is also used by the plants on land that you know so well.

Like grass for cows, microalgae, and cyanobacteria are important sources of food for aquatic animals such as tiny **zooplankton**, fish, or clams. Microalgae and cyanobacteria are particularly important because they produce oxygen for us to breathe and remove carbon dioxide from the air, a gas that is increasing due to human pollution and causing climate change.

WHY ARE HABS POISONOUS?

Most microalgae and cyanobacteria are not poisonous and provide healthy food for animals in the water column as a part of the **aquatic food web**. However, some microalgae and cyanobacteria produce poisons that slow the growth of other microalgae and cyanobacteria and may make humans and animals very sick. The poisons HABs produce can be strong enough to kill or harm plants or animals of any size, including fish, dogs, livestock, sea otters, and whales, just to name a few [1]. People and their pets may get sick after swimming in, drinking, or eating food that came from water containing a HAB. Some HAB poisons can even float in the air we breathe.

HOW DO YOU KNOW IF WATER HAS A HAB?

Identifying a HAB can be difficult without a microscope, but there are some clues you can use (Figure 1). Is the water bright green, brown, or red? Does the surface have a thick mat of green or yellow-green slime? Is there a thick scum or bubbly mass? Are there large, green, irregular chunks that look like flakes floating on the surface of the water? Are dead fish floating in the water? If you can answer yes to any of these questions, then the water may contain a HAB.

HOW DO MICROALGAE AND CYANOBACTERIA BECOME HABS?

Scientists are not sure why some microalgae and cyanobacteria become poisonous HABs. In fact, many of the microalgae and

MICROALGAE

Microalgae are microscopic algae that grow in waterbodies like rivers and oceans. They create sugars for growth using light from the sun, nutrients from the water and carbon dioxide from the air by a process called photosynthesis.

CYANOBACTERIA

Cyanobacteria are microscopic bacteria that live in the water and, like microalgae, produce sugars for growth using light from the sun, nutrients from the water and carbon dioxide from the air by a process called photosynthesis.

ESTUARY

An estuary is a place where the river water meets the ocean water as it moves inland due to the tide. Tides are the daily rise and fall of ocean water due to the attraction of the moon and sun.

[1] https://kids.frontiersin.org/articles/10.3389/frym.2021.611976

ZOOPLANKTON

Zooplankton are tiny animals that float in the water of rivers, lakes, oceans, and estuaries. Some zooplankton are microscopic, but others, like jellyfish are visible with the naked eye.

AQUATIC FOOD WEB

A description of who eats whom in the water, which usually progresses from smaller to larger organisms.

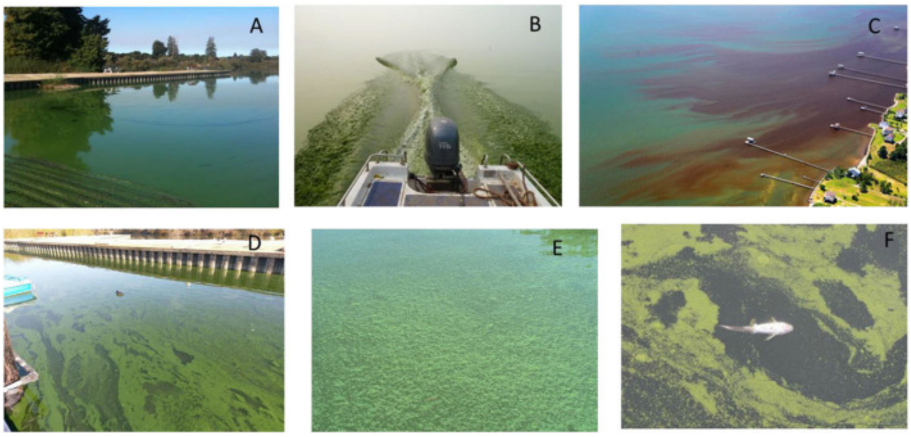


Figure 1

Figure 1

(A) A *Microcystis* bloom in Pinto Lake, CA, USA turned the water bright green. **(B)** The *Microcystis* bloom in Lake Taihu, China becames so thick that it looked like green paint. **(C)** Dinoflagellate blooms turned the water red off the coast of Florida, USA (https://www.cdc.gov/habs/images/habs-homepage-image.jpg). **(D)** *Microcystis* blooms in Pinto Lake, CA, USA. **(E)** *Microcystis* blooms in San Francisco Estuary can look like masses of flakes in the water. **(F)** Dead animals can be a sign of a HAB.

cyanobacteria that form HABs are not always poisonous. Initially, it was thought that HABs made toxins to poison aquatic animals that tried to eat them, like zooplankton. This is a common defense mechanism used against predators by some insects, such as Monarch butterflies. Other scientists found that HAB toxins were produced to protect against bright light. New genetic research suggests that HABs release toxins into the water to poison nearby **bacteria** that compete with them for nutrients. As it turns out, the bacteria *also* release toxins into the water to poison the HABs, creating thousands of biological combat zones within each drop of water! It is likely that HABs make toxins to meet multiple needs.

BACTERIA

Bacteria are microscopic simple single-celled organisms which have an outer cell wall but lack internal structures to hold its cellular components, including its genetic material.

The reasons why some microalgae and cyanobacteria developed the ability to produce poisons remains a scientific mystery. Even within one species, some microalgal and cyanobacteria cells produce toxins, and some do not. Adding to the intrigue is the fact that HABs evolved before their predators did. So, it is unlikely that the original reason for producing poison was as a defense mechanism. Hopefully, scientists will eventually discover why HABs produce poisons, so they can come up with more efficient ways to stop them. Scientists may even discover ways to use the toxins. Many microalgae and cyanobacteria produce substances that have beneficial applications, such as food supplements, anti-cancer drugs, cosmetics, or thickening agents.

HABs usually form in areas where the water is polluted by high concentrations of nutrients from wastewater, fertilizer, or industrial chemicals [2]. Other chemicals used to grow crops or raise livestock can also increase HABs. HABs also tend to form when water temperatures are warm. The rising air temperatures due to climate change are causing water to stay warm longer, allowing HABs to last longer each year. Lastly, when the natural flow of rivers is changed by building dams and reservoirs, rivers flow more slowly, which increases the potential for HABs to accumulate. In San Francisco

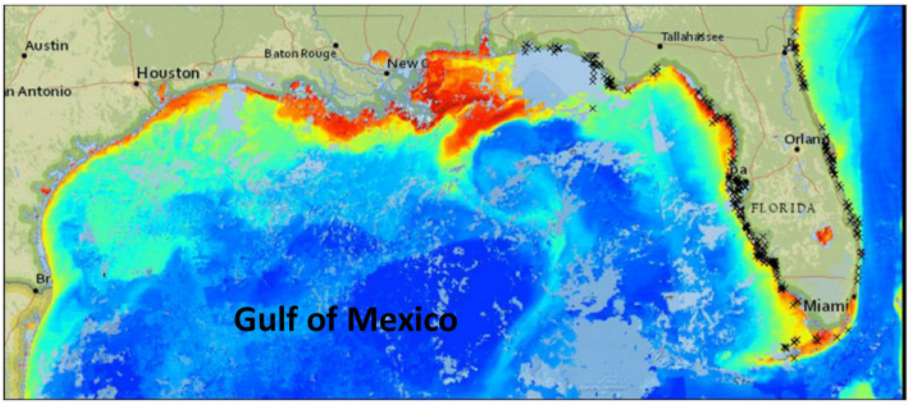


Figure 2

Figure 2

CoastWatch satellite imagery allows scientists to map the presence of HABs formed by the dinoflagellate *Karenia brevis* in the Gulf of Mexico, along the southeast boarder of the United States. Red colors indicate where the dinoflagellate is abundant (Image credit: https://coastwatch.noaa.gov/cw/stories/how-our-data-are-used/harmful-algal-bloom-monitoring-and-forecasting-in-the-gulf-of-mexico.html).

Estuary, where HABs commonly occur, nutrient concentrations and water temperatures are high, and the water moves slowly due to manmade structures such as levees and dams.

WHY ARE WE WORRIED ABOUT HABS IN SAN FRANCISCO ESTUARY?

Scientists in the San Francisco Estuary are worried about HABs because they are occurring more often, getting bigger, lasting longer, and becoming more poisonous, especially during dry years [3]. The warm water temperatures and slow-moving rivers during dry years allow HABs to grow rapidly and accumulate in the estuary's freshwater rivers and salty bays.

In the freshwater rivers of the estuary, cyanobacteria, have formed HABs since 1999. Cyanobacteria HAB species look like little green balls or long strings under a microscope, and they usually turn the water's surface bright green, like paint was spilled on it. A scum on the surface of the water is a common example of what many HABs look like. Scums from some of these HAB blooms are so large that they can be seen by satellites from outer space (Figure 2)!

Cyanobacteria produce poisons that cause cancer, affect the muscles, and impair the growth and survival of non-poisonous microalgae and cyanobacteria, zooplankton, and fish. Studies in San Francisco Estuary showed that the poisons produced by one type of cyanobacteria called *Microcystis* accumulate in the tissues of young fish, clams, zooplankton, and even worms. Fish exposed to *Microcystis* were unhealthy and developed liver disease [4]. Sometimes HABs even affect animals through the bacteria that surround them. In one study, *Microcystis* poisoned baby fish by increasing the amount of *Aeromonas* bacteria, a type of bacteria that kills fish [5].

Cyanobacteria poisons can also make people sick if they accidentally drink the water when swimming, or if they drink water that is not correctly treated. In 2014, a state of emergency occurred in Ohio, USA, when *Microcystis* from Lake Erie poisoned the drinking water of a half a million people[2]. The *Microcystis* HAB in the rivers of San Francisco Estuary could affect the water used by up to 25 million people!

[2] https://www.npr.org/sections/health-shots/2017/11/09/563073022/algae-contaminates-drinking-water

In the salty, shallow bays of the estuary and areas close to the ocean, we also find HABs caused by types of microalgae known as **dinoflagellates** and **diatoms**. Dinoflagellates often look like soccer balls with tails wrapped around their middles. They can turn the water bright red or brown during the day and make it glow at night. Diatoms are encased in silica shells that look like tiny, carved glass boxes. These microalgae turn the water bright green and can make the water look bubbly near the shore.

DINOFLAGELLATES

Dinoflagellates are microalgae in the phylum Dinoflagellata and swim in the water using two tail-like flagella. Although they can grow using photosynthesis, they can also eat other microalgae.

DIATOMS

Diatoms are microalgae in the phylum Bacillariophyta. They have a shell made of silica that looks like a tiny glass box. Because their shell is heavy, diatoms often live on the bottom of rivers or lakes and need lots of mixing by wind and tide to stay in the water column.

Dinoflagellate and diatom HABs can accumulate in seafood, including fish, clams, and oysters, making these foods poisonous. Humans, marine mammals, and birds that eat these shellfish can become sick [6]! The presence of HAB poisons in food also affects the economy, through impacts on fishery-related businesses like the shellfish industry. When fish are poisonous, fishermen cannot sell them to a market, which in turn cannot sell fish to restaurants, which then cannot sell fish to their customers.

HOW CAN YOU BECOME A HAB WARRIOR?

You can be a HAB warrior by helping to protect others and reduce the spread of HABs. Learn how to identify potential HABs. If you see a HAB, keep yourself and your animals away from it, and warn others. Contact a local water agency or your school to alert them to the potential problem. Join a citizen science group that collects water at local lakes to be tested for HABs. Stay alert to reports of HABs in the news or signs at local waterways and be sure the fish and shellfish you eat come from areas without HABs (Figure 3).

You can also fight against HABs by reducing pollution. Poisonous microalgae and cyanobacteria occur where nutrients from industrial pollution and fertilizer runoff are high. So, try to reduce the amount of nutrients and chemicals in the water by recycling and careful use of chemicals. Avoid applying large quantities of fertilizers, which can run into waterways after heavy rains. Reduce the production of gases like carbon dioxide that heat the air by reducing energy use. Turn off lights and electrical devices when not in use, reduce fossil fuel use by walking, biking, or using public transportation, and recycle.

Finally, consider being a HAB scientist! We need people like you to develop models and warning systems to protect people from HABs, determine why HABs become poisonous, develop technologies to

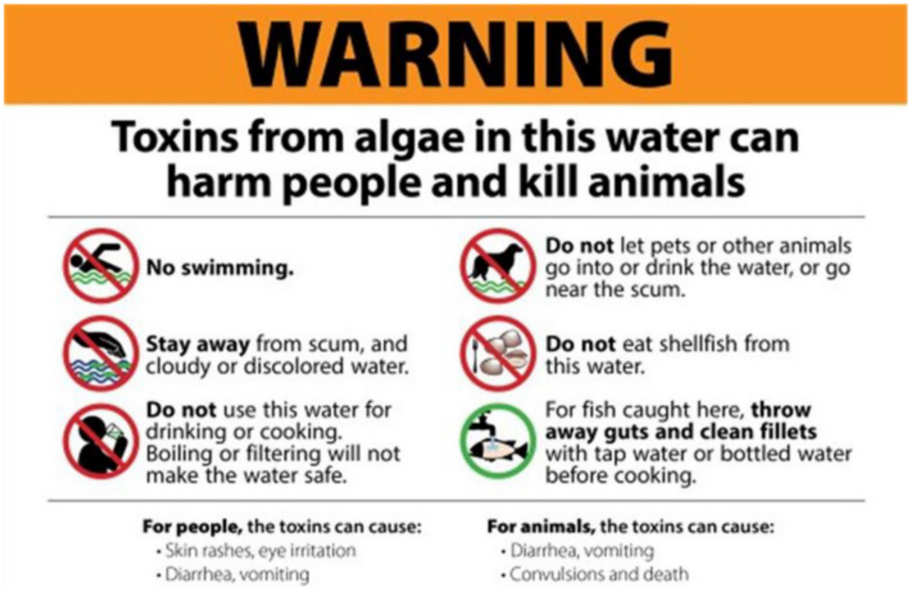


Figure 3

Figure 3

Watch for warning symbols and signs like these near waterways, to know when it is not safe to enter or use the water (Image credit: https://mywaterquality.ca.gov/habs/).

monitor HABs and make them less toxic, and importantly, to determine how HABs can be prevented. If both scientists and the public work together as HAB warriors, we can preserve the health of waterways, aquatic ecosystems, animals, and humans!

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CONFLICT OF INTEREST: TO is the director at Bend Genetics, LLC.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

MEHA, AGE: 15
Hey, I am a sophomore in high school, and looking forward to a career in medicine. My hobbies include drawing, tennis, and just hanging out with friends! I also love to volunteer and give back to my community. I am excited to be a part of Frontiers for Young Minds, as I want my peers and other students to be able to access these great scientific accomplishments made every day.

NIVEDITA, AGE: 14
Hi I am Nivedita, my pronouns are she/her/hers, and I am excited to start this year off! A little about me, I love listening to music in my free time (Frank Ocean is a favorite ☺) and I like to draw when I can. I like hanging out my friends, and my favorite subject is chemistry!

SHREEYA, AGE: 11

Hi my name is Shreeya. I live with my sister and my parents. In my free time I like to walk with friends, play board games, and doing karate. During this time, I have been keeping myself busy by talking with my friends, reading Harry Potter books, and finishing a 3D Hogwarts Puzzle.

SHRIYA, AGE: 13

Hi, my name is Shriya. I live in the U.S. I am in eighth grade, and my favorite subjects are science and math. In my free time, I like to dance and do art. I just started working with Frontiers for Young Minds, and am very excited to continue!

AUTHORS

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I am a Ph.D. ecologist with a specialty in phytoplankton and work as a senior scientist for the State of California, USA. My research includes the growth, causes, and ecosystem impacts associated with *Microcystis* harmful algal blooms in the freshwater reaches of San Francisco Estuary. I also study the phytoplankton in rivers and wetlands within the estuary in response to environmental conditions, including climate change. In my free time, I enjoy watching changes in phytoplankton blooms as I kayak through rivers and lakes near home. *Peggy.Lehman@water.ca.gov. To find out more about my work see †orcid.org/0000-0001-9556-0542.

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I am an assistant professor in aquatic toxicology at the University of California, Davis. I have been investigating various ecological issues, including impacts of contaminants like pharmaceutical and personal care products, algal toxins, and pesticides, on aquatic organisms such as phytoplankton, copepods, and fishes. My goal is to reduce ecological issues using scientific knowledge. Are you interested in water quality? Please email me: tkurobe@ucdavis.edu; †orcid.org/0000-0003-3906-1989.

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I am a public health microbiologist interested in studying the feedback between human activities that make the environment "sick"—such as nutrient pollution that causes algal blooms—and how these blooms in turn have the potential to make humans sick. I founded a water quality laboratory in Sacramento, CA that is dedicated to all aspects of harmful algal bloom testing. Please email me with any questions at: ottentim@bendgenetics.com

MELISSA B. PEACOCK

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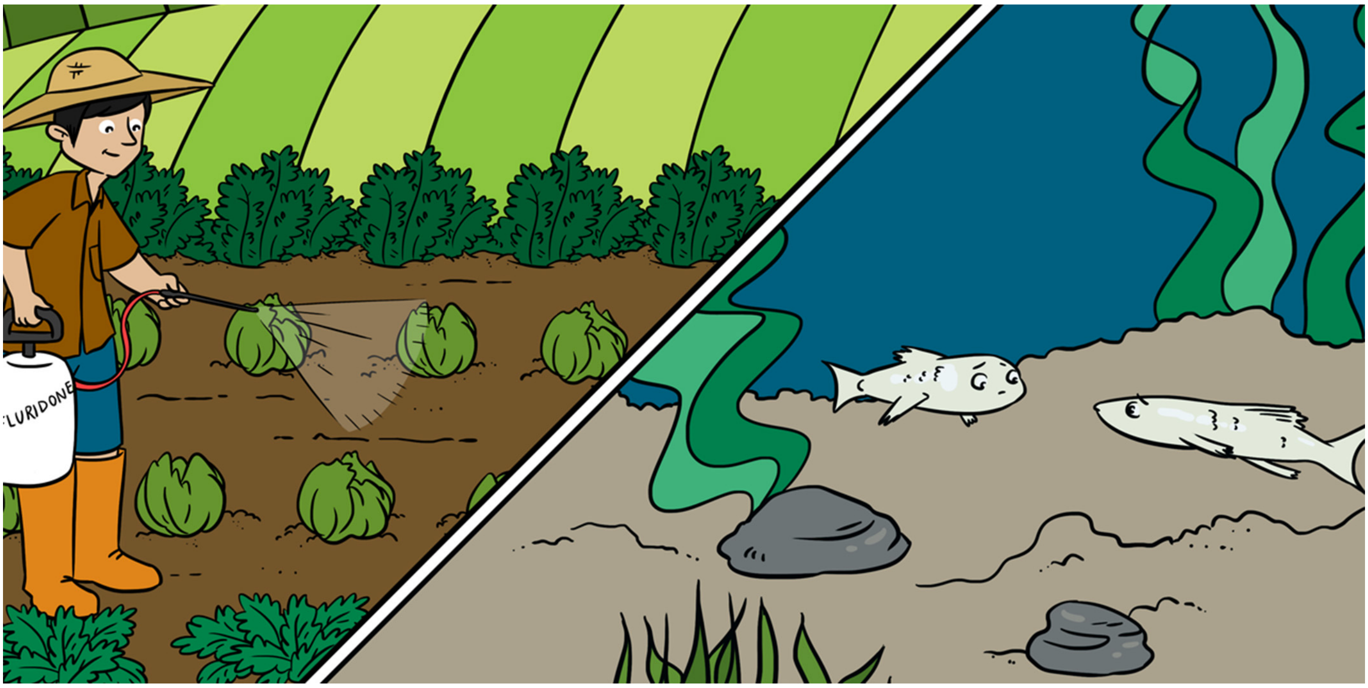

WHAT DOES NOT KILL CAN WEAKEN: HOW HERBICIDES IMPACT FISH IN THE SAN FRANCISCO ESTUARY

Khiet Huynh**, Tomofumi Kurobe*†, Marie Stillway, Chelsea Lam and Swee Teh

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YOUNG REVIEWERS:

SAMEEN
AGE: 15

ZAINAB
AGE: 12

Farmers in the San Francisco Estuary have been using increasing amounts of weed killers, also called herbicides, on their farms. Herbicides kill unwanted weeds without hurting food crops. However, did you know that herbicides can hurt fish as well, especially those that live in the Estuary, like delta smelt? Delta smelt are small, translucent fish that only occur in the San Francisco Estuary. In the past, delta smelt could be found everywhere in the Estuary. However, they are currently threatened with extinction, largely due to human activities. In this study, we tested the toxicity of fluridone, a commonly used herbicide found in the San Francisco Estuary, on delta smelt. None of the fish died from fluridone, but we found that it weakened them, even after as little as 6 h of exposure!

WHAT ARE WEED KILLERS AND HOW DO THEY GET INTO THE SAN FRANCISCO ESTUARY?

Weeds are always a problem for farmers and homeowners everywhere. They steal water from crops and prevent crops from growing well. Pulling weeds out of the soil by hand can be tiring and disappointing—some weeds come right back! In the early twentieth century, scientists began to develop chemicals called weed killers or **herbicides**, which kill weeds without hurting crops. Now, most farmers in the world use herbicides because they are very effective and easy to use.

HERBICIDE

A substance that is toxic to plants, used to kill unwanted plants.

ESTUARY

A partially enclosed coastal body of brackish water with one or more rivers or streams flowing into it, and with a free connection to the ocean.

The San Francisco **Estuary** is surrounded by a lot of farmland, and most farmers in the area spray herbicides onto their crops. Some of these herbicides remain in the soil. Then, rain or snow washes them into canals, streams, and rivers, and eventually into the Estuary. Some herbicides are even applied directly to the rivers in the Estuary. For example, in 2014, the San Francisco Estuary suffered a terrible drought. Low water levels and high temperatures allowed aquatic weeds to grow rapidly. Some of these plants were introduced by human activities, like the release of aquarium plants into the river. Their growth dominated other native plants, altered water flow, and blocked the movement of boats in the river. To resolve this problem, local agencies used several herbicides, including **fluridone**, to kill the aquatic weeds.

FLURIDONE

A chemicals used to get rid of aquatic plants.

As researchers monitored water quality in the San Francisco Estuary, they detected low levels of these herbicides. Since herbicides are designed to kill only aquatic plants, low levels of fluridone were thought to be safe for aquatic animals. However, we were suspicious that low levels of fluridone might make fish sick, without killing them. Several research studies reported that low levels of herbicides prevented Atlantic salmon and rainbow trout from growing [1, 2]. We hypothesized that fluridone was causing similar negative effects on the growth of native fish species in the San Francisco Estuary.

HOW DID WE TEST THE EFFECTS OF FLURIDONE ON FISH?

To test our hypothesis, we used delta smelt as our test subject (Figure 1). The delta smelt is a small **pelagic fish** that smells like cucumbers and can only be found in the San Francisco Estuary. Since the Estuary is the only place that they live, any change in the Estuary can harm their entire population. In fact, the delta smelt is currently an endangered fish species that is nearing extinction, largely due to human activities. By testing the toxicity of herbicides on delta smelt, we hoped to find a way to protect their population.

PELAGIC FISH

A fish that stays in the upper and middle layers of a body of water, not close to the bottom or near the shore.

Figure 1

Figure 1

The delta smelt is a species of fish found only in the San Francisco Estuary (Image credit: UC Davis Fish Culture and Conservation Laboratory).

BIOMARKER

A measurable substance in an organism that indicates some internal change in the body, such as disease, infection, or environmental exposure to poisons.

HORMONE

A messenger substance produced by living organisms that stimulates cells or organs into action.

ANTIOXIDANT

A substance that prevent oxygen group to be added to other substances.

ENZYME

A substance produced by living organisms that helps a chemical reaction to happen more quickly in the body.

In medicine, general symptoms like a headache or stomachache are often not enough for doctors to diagnose a patient accurately. Doctors often need to further examine any chemical changes that are happening within the patient's body. Since we cannot look at these chemicals with our naked eyes, **biomarkers** are the tools we use to detect any internal chemical changes. A biomarker is a chemical or a substance in the body that we can measure to evaluate how sick the body is. When we are sick or in distress, our bodies fight against the illness or injury, which changes the levels of biomarkers in our bodies. By looking at these changes, we can accurately diagnose what is happening within the body. For example, doctors frequently look at chemical changes in the blood. If they detect a high level of insulin in the blood, they can predict that the person may have a disease called diabetes. In this way, insulin acts as a biomarker that predicts diabetes. For our study, we used biomarkers to determine whether fluridone caused any chemical changes in fish.

To prepare for the experiment, we used 20-liter buckets to hold the fish. They were filled with fresh water from the nearby river where delta smelt live, and we placed them in a water bath where the temperature was kept at 15.7°C with a water heater. Delta smelt grow well when the water temperature is around 16°C, so we adjusted the bath to that temperature to keep them happy. We divided the buckets into two groups: experimental and control. For the buckets in the experimental group, we added fluridone to the water. The buckets in the control group only contained clean water, without fluridone. Then, we put in 10 adult fish into each bucket and attached a bubbler to each bucket so the fish would have air to breathe. After 6 h, we collected the fish from both the experimental and control buckets and measured three biomarkers: a growth **hormone**, an **antioxidant**, and a brain **enzyme**. The growth hormone lets us know how well fish will grow and mature; the antioxidant indicates if the fishes' bodies are under stress or not; and the brain enzyme tells us if the fishes' brains are working properly. We compared measurements of the three biomarkers from both groups and looked for any differences between them (Figure 2).

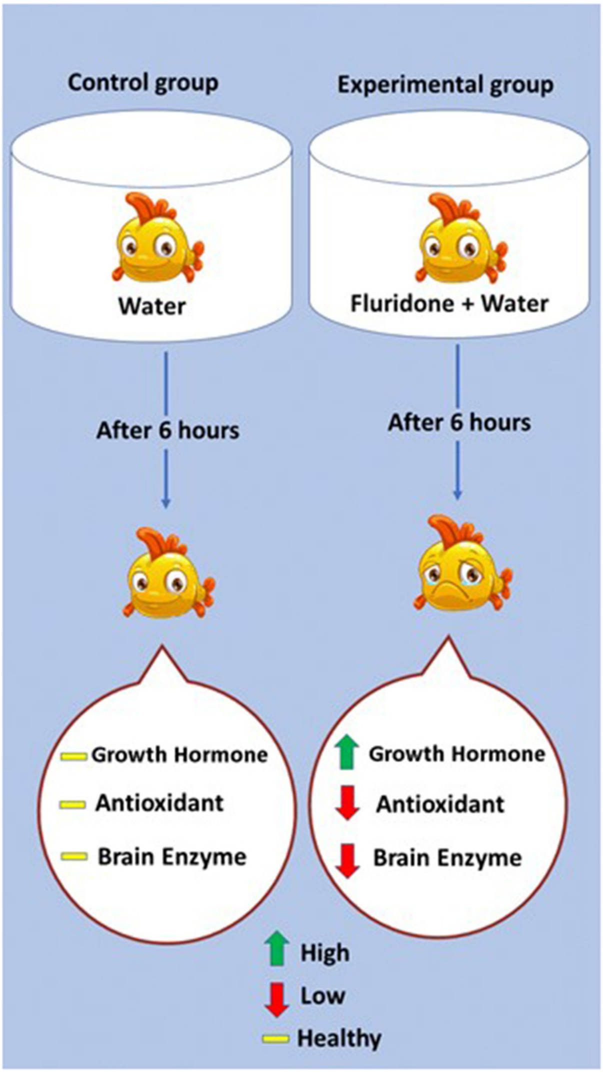

Figure 2

Figure 2

In our experiment, we tested whether a 6 h exposure to fluridone affected three biomarkers in delta smelt. All fish survived after the exposure. However, we found fish in experimental group have higher level of sex hormone and lower level of antioxidant and brain enzyme comparing to control group which told us that fluridone is making fish sick.

IS FLURIDONE BAD FOR DELTA SMELT?

All fish in the experimental group survived after 6 h of exposure to fluridone! This was good news. However, the levels of the three biomarkers told us that the fluridone made the fish sick, even though we could not see it.

We found that fluridone increased the level of growth hormone in delta smelt. Growth hormone controls the rate at which a fish matures. It causes female fish to start making eggs and triggers changes in behavior, skin color, and fin shape, all of which distinguish female fish from male fish. High levels of growth hormone can be bad for both female and male fish, preventing them from maturing correctly or reproducing properly. High levels of growth hormones cause female delta smelt to lay fewer, poor-quality eggs. Exposure to high level of growth hormone can be so strong that a male fish can change into a female fish!

We also observed that fluridone lowered the level of brain enzymes in the brains of delta smelt. The brain controls many bodily mechanisms by making chemicals that signal other parts of the body. Brain enzymes control how strong these signals are. A decreased level of brain enzymes could slow the activities of delta smelt, such as finding food or swimming away from predators. Therefore, lower brain enzymes could mean lower survival in the Estuary.

Last, we found that fluridone lowered the level of antioxidant in fish. Bodies produce a lot of chemicals throughout the day, many of which are vital to the body's functions. However, too much of even good chemicals can put a lot of stress on the body. Antioxidants help get rid of the extra chemicals and maintain a healthy balance of chemicals in the body. Without antioxidants, chemicals begin to build up. Long exposure to fluridone might result in high levels of chemicals that could injure the internal organs of the fish (like the liver or kidneys), weaken the fish, and eventually cause them to die.

WHAT DID WE CONCLUDE?

This study confirmed that low levels of fluridone did not kill delta smelt. However, we found that exposure to this herbicide for only 6 h caused sickness in delta smelt that might weaken their ability to survive in the San Francisco Estuary (Figure 3). Exposure to fluridone for longer than 6 h might cause severe damage to fish organs, which may even kill fish. Longer exposure to fluridone may also affect the ability of delta smelt to reproduce, which would mean fewer delta smelt in the Estuary.

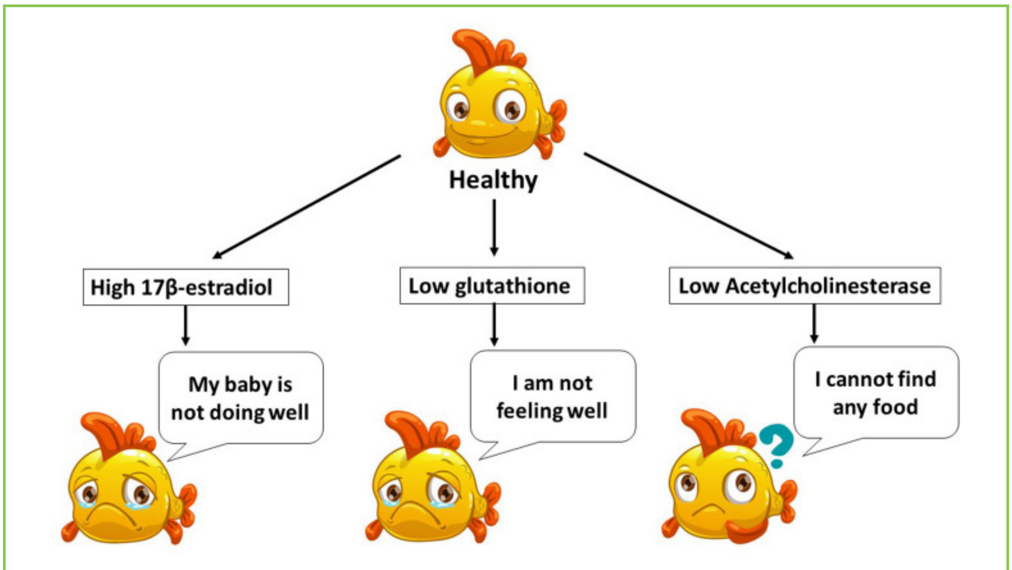

Figure 3

Figure 3

Potential negative impacts of fluridone on delta smelt.

Researchers and local environmental agencies have reported that populations of other pelagic fish species, like striped bass, threadfin shad, and longfin smelt, are also declining in the San Francisco Estuary. The cause of these declines is not known, but our study suggests that herbicides like fluridone could weaken the health of other fishes in the Estuary. Unfortunately, new types of herbicides are being added to the San Francisco Estuary all the time, and we do not know how they will affect the aquatic animals.

WHAT CAN WE DO?

We all agree that chemicals like herbicides can make our lives a lot easier. However, we sometimes get a little bit careless with them. Overuse of chemicals can end up polluting the canals, rivers, or streams that we depend on as water sources. Products like herbicides and pesticides need to be used in moderation to keep our water safe. Understanding how these chemicals enter our waters is important, so farmers and other people who use herbicides can take steps to prevent this pollution from happening. Public awareness campaigns can be created to help inform the farmers about the environmental effects of overusing herbicides. By helping everyone to understand the negative effects that herbicides can have on local fish species, we will protect not only our own health but the health of the many fish in the San Francisco Estuary and other important waters.

ORIGINAL SOURCE ARTICLE

Jin, J., Kurobe, T., Ramírez-Duarte, W., Bolotaolo, M., Lam, C., Pandey, P., et al. 2018. Sub-lethal effects of herbicides penoxsulam, imazamox, fluridone and glyphosate on Delta Smelt (*Hypomesus transpacificus*). *Aquat. Toxicol*. 197:79–88. doi: 10.1016/j.aquatox.2018.01.019

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

SAMEEN, AGE: 15
Hello, I am Sameen from and I have a strong interest in science subjects, but I like studying biology more. I love to explore natural processes, particularly in aquatic ecosystems. I love to read science articles in the newspaper and learn new languages. Besides, I wish to participate in environmental clubs and field trips. I want to study freshwater ecosystems and molecular biology when I grow up.

ZAINAB, AGE: 12
Hi, My name is Zainab, and I live in a small village. I am excited about species relationships and environmental changes, perhaps why I love knowing about species and ecosystem biology. Apart from that, I want to learn about the history of species and their environment. I like to go to the countryside and see the variety of land plants and animal species. I am also willing for online learning activities related to biology and ecosystems.

AUTHORS

KHIET HUYNH
I am a lab assistant working in the Aquatic Health Program of the University of California, Davis. I am studying the health of delta smelt in the wild and trying to figure out what their ideal habitat is. My goal is to preserve the delta smelt and hopefully recover their population in the future. *khihuynh@ucdavis.edu

TOMOFUMI KUROBE
I am an assistant professor in aquatic toxicology at the University of California, Davis. I have been investigating various ecological issues including impacts of contaminants (e.g., pharmaceutical and personal care products, algal toxins, pesticides) on aquatic

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MARIE STILLWAY

I am an environmental toxicologist at University of California, Davis. My research focus is assessing water quality and ecosystem health. I evaluate the effects and interactions of environmental stressors (e.g., pesticides, herbicides, and chemicals of emerging concern) on fishes, invertebrates, and algal species of the San Francisco Bay-Delta through toxicity testing. These experiments are conducted both in the lab and in the field. I started working here as an undergrad student and now manage the Aquatic Toxicology Laboratory.

CHELSEA LAM

I am a graduate student at University of California, Davis. My research focus is studying about phytoplankton communities. I assess the effects and interactions of pesticides and nutrient inputs from human activities on algal species of the San Francisco Bay-Delta.

SWEE TEH

Swee Teh is director of the Aquatic Health Program at the School of Veterinary Medicine, University of California, Davis. He is also director of the Aquatic Toxicology Laboratory; a state-certified laboratory engaged in monitoring and assessing ambient water quality and aquatic ecosystem health. He has published over 100 research articles. His research interests are aquatic health, including the effects of polluting chemicals on aquatic organisms and ecosystems. He has been married to his wife Foo-Ching for 39 years. They have 2 grown children who live in California.

EARTH AND ITS RESOURCES
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TOXIC MEALS FOR SEABIRDS AND SEALS: MONITORING MERCURY IN THE SAN FRANCISCO BAY

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YOUNG REVIEWER:

ETHAN
AGE: 8

Mercury is a metal pollutant that travels thousands of miles through air and water. It flows along rivers to lakes, estuaries, and the sea, cycling between animals and their environments. Extensive mercury mining during the Gold Rush left lasting impacts on the San Francisco Bay Delta, one of California's largest wetland habitats and home to thousands of species. Burning fossil fuels in cities like San Francisco also releases mercury, leading to its buildup in local food chains. Mercury accumulates from plankton to fish to top predators like sharks and seals, where it reaches potentially harmful levels. Mercury never fully breaks down and continues cycling in ecosystems, even reaching migratory animals living offshore in the Pacific Ocean. Scientists collect samples from wildlife to uncover clues about mercury sources and threats to human health. This article explains

the mercury problem and why we track this invisible pollutant in the San Francisco Bay.

WHY IS MERCURY SO HIGH IN THE SAN FRANCISCO BAY?

The answer to why mercury levels are so high in the San Francisco Bay (SFB) lies in a story of grit, greed, and gold. Gold discovery in the Sierra Nevada mountains during the mid-1800s drove thousands of people to California to stake their claims. The landscape was quickly changed as tunnels were dug, rivers dammed, and forests logged. In addition to altering the land forever, the California Gold Rush left behind an unexpected and invisible toxic partner: mercury. People used liquid mercury, a naturally occurring element that sticks to gold, to collect gold from mined rock and river sediment. Mercury waste was carried into streams and rivers and swept out to the SFB, a critical habitat for wildlife and important source of seafood. Though the Gold Rush took place over 100 years ago, rivers still carry mercury from remote areas to the Bay [1]. This historic mining, combined with other sources, have led to mercury levels high enough to threaten SFB wildlife and prompt seafood warnings [2].

ANAEROBIC BACTERIA

Single-celled bacteria that do not depend on oxygen to survive. Some anaerobic bacteria that live in aquatic sediments produce methylmercury.

METHYLMERCURY

A mercury atom attached to a chemical group called a methyl group. This form is absorbed into plants and animals and builds up in food chains.

BIOACCUMULATION

The gradual increase of a toxin or substance (such as methylmercury) in an individual's tissues over time.

BIOMAGNIFICATION

The increase in levels of toxins or substances in animals that feed at higher levels of the food chain.

THE MERCURY CYCLE

How is mercury that was used over a century ago still at high levels in the SFB? Mercury is a toxic metal element and is impossible to destroy. It gets released through natural processes and human activities. Natural sources of mercury include volcanoes, forest fires, and hydrothermal vents in the ocean floor. Humans release mercury into the environment by burning fossil fuels like petroleum and coal. Mercury easily evaporates into the atmosphere and can travel around the world before clinging to water droplets and falling back to Earth in rain and snow. When mercury collects in water bodies like lakes, rivers, and bays, certain **anaerobic bacteria** (single-celled organisms that do not depend on oxygen to survive) transform it into **methylmercury**. This especially toxic form can be absorbed by plants and small organisms, then accumulate in the food chain (Figure 1).

When it comes to studying pollutants, there are two important concepts: **bioaccumulation** and **biomagnification** (Figure 1). Animals absorb more and more mercury from their food, and it builds up in tissues as they age. This process is called bioaccumulation. Small fish feeding at the bottom of the SFB food chain, like anchovies and smelt, have lower mercury levels than larger predatory fish like halibut. Top predators like sharks and harbor seals have the highest mercury levels in their bodies. Increasing mercury levels with increasing steps in the food chain is called biomagnification.

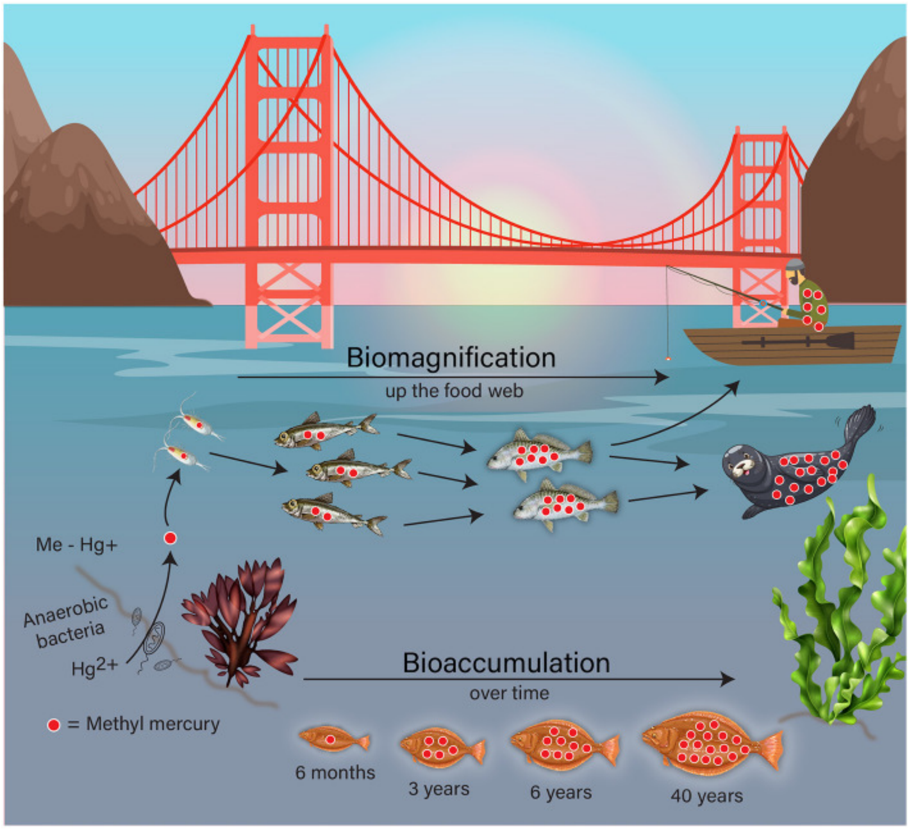

Figure 1

Figure 1

Elemental mercury (Hg^{2+}) is converted by anaerobic bacteria in sediments to methylmercury (Me - Hg^{+}), which is absorbed by plants and small aquatic organisms. Methylmercury accumulates up the food chain, reaching higher levels in top aquatic predators such as seals, through a process called biomagnification. Methylmercury also increases within an individual animal's body over time as it ages. This is bioaccumulation (Image credit: Irma Macias, Metropolitan Water District (MWD) of Southern California External Affairs).

MONITORING MERCURY IN SAN FRANCISCO BAY WILDLIFE

Because of historic mercury mining, SFB Estuary prey fish have mercury levels three to six times higher than similar species on the U.S. East Coast [3]. The U.S. Environmental Protection Agency considers fish with <0.2 milligrams of mercury per kilogram of muscle to be safe for human consumption [2]. Some large, long-lived fish such as white sturgeon and striped bass have mercury levels twice as high as this limit [2]! Scientists care about mercury levels in fish to protect human health, but they also care about wildlife health. One study estimates that one in four fish from the SFB have mercury levels high enough to harm their growth, reproduction, and survival [3]. Some seabirds such as terns have enough toxic mercury in their blood to harm their reproduction. Mercury can also pass from a mother bird to her eggs! Some mercury levels found in SFB tern eggs make scientists worry about whether they can hatch and survive.

Researchers measure mercury and look for health effects in top predators like seabirds and seals because these animals are more likely to have high methylmercury levels. Methylmercury tends to build up in body parts containing keratin, a hard, waterproof protein that makes up hair and fingernails. Seal fur and bird feathers are

Figure 2

Figure 2

Different fish contain different levels of mercury and certain people, including growing kids like you, are more likely to be harmed from eating food containing mercury. Be sure to check local advisories to make sure the type and amount of fish you are eating is safe (Image credit: Irma Macias, MWD of Southern California External Affairs, designed with advice from the California Office of Environmental Health Hazard Assessment).

also made of keratin, so they are excellent samples for monitoring methylmercury [3]. Scientists also test blood, muscle, fat, and feces to assess methylmercury levels in the body. By comparing levels among various animal populations, scientists map mercury across locations and habitats to track ecosystem health and identify new "hot-spots," or areas with high mercury levels.

WHICH FISH ARE SAFE TO EAT?

The benefits of eating some fish can outweigh the risks. Fish provide important nutrients like omega-3 fatty acids, which are good fats needed for brain and heart health. It is all about moderation; *how much* and *what types* of fish you eat. Methylmercury travels from the digestive system to the blood and easily enters many cells in the body, including the brain. Babies and children are considered sensitive groups because their brains are still growing, so pregnant or breastfeeding women and kids under 18 should be careful about their seafood consumption [1]. The California Office of Environmental Health Assessment[1] monitors mercury levels in the SFB and recommends how much seafood from specific locations can be safely

[1] Available online at: https://oehha.ca.gov/fish/advisories.

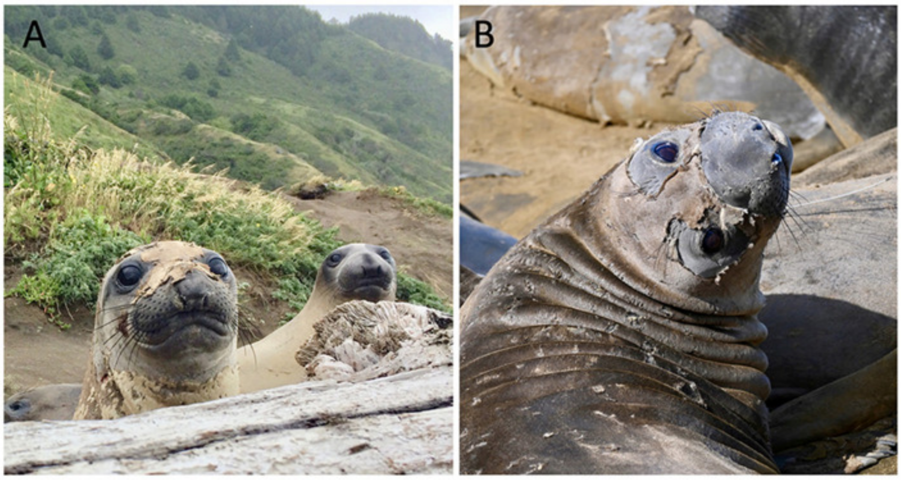

Figure 3

Figure 3

These photos show the elephant seal catastrophic molt. **(A)** A juvenile elephant seal going through its yearly molt next to a freshly-molted friend. **(B)** Another molting seal shedding its mercury-rich fur (These photos were taken under NMFS Permit #19108. Credit: Costa Lab/Claire Nasr and Dan Costa).

eaten in the "Good Catch California" advisory program (Figure 2). For example, rock crab and chinook salmon are low enough in mercury that sensitive groups can eat two servings a week. On the other hand, sharks and surfperch have such high mercury levels that they should never be eaten by sensitive groups. It is always good to know which fish are safe, so check seafood advisories before eating fish from your local waterbodies. Of course, fish are caught and shipped all over the world. The Monterey Bay Aquarium's Seafood Watch program[2] can help you make safe and sustainable choices when looking through your restaurant menu.

[2] Available online at: https://www.seafoodwatch.org/.

WILDLIFE PARTICIPATE IN THE MERCURY CYCLE

If mercury in the body cannot be completely broken down, where does it go next? The more we study mercury, the more we discover interesting roles animals play in transporting mercury between habitats and locations. Migrating animals that travel long distances each season assist in mercury recycling by feeding in one place and transporting mercury with them to new locations. Salmon, for example, hatch in freshwater before migrating to the ocean, where they feed on fish that contain mercury [4]. When it is time to find a mate, they (and mercury they built up) swim up rivers to reproduce. Their life cycle is then complete. Salmon may die, but their mercury lives on! Their bodies release mercury back into the environment [4], where it can be picked up by animals that eat them. Hatched salmon from rivers also pick up mercury before migrating back out to sea. Imagine the thousands and thousands of salmon migrating up the Sacramento and San Joaquin rivers to reproduce each year, bringing mercury with them.

Mercury released from historic mining and ongoing human activities extends beyond the SFB Delta, reaching animals that live and feed offshore in the Pacific Ocean. Northern elephant seals spend most of their time in the open ocean, diving and feeding on mercury-rich fish and squid. Each year, thousands of seals return to colonies in California to "molt," or shed their coats (just like dogs and cats shed their fur). But instead of slowly shedding year-round, elephant seals go through what is called a catastrophic molt (Figure 3), during which they shed and regrow their skin and hair in just a few weeks! This means a year's worth of mercury-rich hair from thousands of seals is quickly dropped off on beaches. Molted hair contains 3.5 milligrams of mercury per kilogram of hair, which is 10 times higher than mercury levels in fish that are safe for humans to eat! The molted hair breaks apart, leading to seawater mercury over 10 times higher than seawater found at nearby beaches without elephant seals [5]. Remember how mercury never breaks down? It becomes available to animals at the base of the food chain, like crabs and mussels, who start the bioaccumulation chain all over again. It is important for scientists to identify these mercury recycling centers because seafood in these areas could have toxic mercury levels and endanger human health.

ONE PLANET, ONE HEALTH

The One Health concept is that humans, animals, and their environments are closely linked. If we work to make one healthier, the others become healthier too. If one is sick, it means others are at risk of getting sick as well. Certain animal species share food, water, and habitats with human populations. We call these **indicator species** because they are exposed to similar pollutants and can signal if there is a problem in the environment. Marine mammals and seabirds serve as important indicator species in the SFB. When we consider how widespread mercury and other pollutants are, keeping an eye on their presence in wildlife is essential for keeping an eye on the health of the environment and the humans that share it. This is a big problem, so what can you do? To help reduce mercury emissions, participate in activities that use less fossil fuels, like biking or walking instead of getting a car ride. To protect the safety of your environment, reduce, reuse, and recycle mercury-containing products such as batteries and fluorescent light bulbs. To protect your safety, be conscious of your seafood consumption and help your family support sustainable aquaculture and fisheries with low mercury levels. Everyone's actions make a difference.

INDICATOR SPECIES

Species used to study the health of habitats. They are usually the first species affected or the most sensitive to environmental changes, like decreasing water quality or food availability.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER

ETHAN, AGE: 8
My name is Ethan. I play the piano and take martial arts classes. I like science and reading. My favorite thing to do is to celebrate my friends' birthday parties and to

play soccer with my team. I have two miniature Holland Lop bunnies. I love sharks and when I am old, I want to be a conservation biologist.

AUTHORS

JENNIFER COSSABOON

I am a doctoral student researcher in the Aquatic Health Program at the University of California, Davis School of Veterinary Medicine. My fascination with wildlife health and toxicology began while working with seals and sea lions in Monterey Bay and Alaska. I was inspired to earn an M.S. in Public Health Sciences from San Diego State University, where I tracked emerging pollutants in Southern California marine mammal species and the endangered California condor. I am now pursuing a D.V.M./Ph.D. to pair research tools with clinical skills and continue researching the role of contaminants in animal and human diseases. *jcossaboon@ucdavis.edu

SHAWN ACUÑA

Shawn Acuña is a Senior Resource Specialist for Metropolitan Water District of Southern California. He has almost 20 years of experience in the field of fish biology and environmental science. He has a B.S. in Aquatic Biology from UC Santa Barbara and an M.S. in Animal Biology and Ph.D., in Ecology from UC Davis. He has expertise in gross pathology, histopathology, and nutrition and health biomarkers and has conducted field and laboratory studies on environmental stressors. His currently works on stressors and stressor effects in the San Francisco Estuary to inform sustainable management of the estuary.

BRUCE G. HAMMOCK

I am an aquatic biologist at UC Davis. I am particularly interested in applying science—including ecology, toxicology, hydrology, and statistical modeling—to environmental problems. Some of my recent work has linked the proximity and extent of tidal wetlands to the foraging success of an imperiled fish. Another recent study explored the causes of the collapse of the pelagic food web in the San Francisco Estuary. Most recently I compared the sensitivities of a wide range of biomarkers to fasting in Delta smelt, a locally endemic, imperiled fish.

TOMOFUMI KUROBE

I am an assistant professor in aquatic toxicology at the University of California, Davis. I have been investigating various ecological issues including impacts of contaminants (e.g., pharmaceutical and personal care products, algal toxins, pesticides) on aquatic organisms such as phytoplankton, copepods, and fishes. My goal is to mitigate ecological issues using scientific knowledge. Are you interested in water quality? Please email me: tkurobe@ucdavis.edu. ORCID ID: https://orcid.org/0000-0003-3906-1989.

MARIE STILLWAY

I am an environmental toxicologist at U.C. Davis. My research focus is assessing ambient water quality and ecosystem health. I evaluate the effects and interactions of environmental stressors (e.g., pesticides, herbicides, and chemicals of emerging concern) on Delta fishes, invertebrates, and algal species through the use of toxicity testing. These experiments are conducted both in the lab and in the field. I have been with UC Davis for more than 20 years, first getting my bachelor's degree in English, then my master's degree in Animal Biology. I started working here as an undergrad student and now manage the Aquatic Toxicology Laboratory.

SWEE J. TEH

Swee Teh, Ph.D. is director of the Aquatic Health Program at the University of California-Davis School of Veterinary Medicine. He is also director of the Aquatic Toxicology Laboratory; a state-certified laboratory engaged in monitoring and assessing ambient water quality and aquatic ecosystem health. He has published over 100 research articles in peer-reviewed journals. His research interests are aquatic health, including the effects and interactions of physicochemical and contaminant stressors (toxicant, carcinogen, and endocrine disruptor) on aquatic organisms and ecosystems. He has been married to his wife Foo-Ching for 39 years. They have two grown children who live in California.

EARTH AND ITS RESOURCES
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HOW ARE MICROPLASTICS INVADING THE WORLD?

***Charlene Lujan-Vega*[1,2*], *José Luis Ortega-Alfaro*[2,3], *Jennifer Cossaboon*[1], *Shawn Acuña*[4] and *Swee J. Teh*[1]**

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[2] *Microplastic Fauna Peru Project, Lima, Peru*
[3] *Laboratory of Ecology and Animal Biodiversity, Universidad Nacional Federico Villarreal, Lima, Peru*
[4] *Metropolitan Water District of Southern California, Sacramento, CA, United States*

YOUNG REVIEWERS:

CORTE MADERA SCHOOL
AGES: 10–11

Microplastics are tiny plastic pieces, <5 mm, which is smaller than a pencil eraser. Did you know that you can find microplastics everywhere? They are in the air, water, soil, and within living creatures. You can find them from the deep sea to the snow in the Arctic. You can find them across beaches in California, and in the San Francisco Bay waters. Many living organisms ranging from zooplankton to whales contain microplastics in their bodies, including aquatic creatures from California. In this article, you will learn about the origin of microplastics, where you can find them, why they are a concern, how they can affect the Sacramento-San Joaquin Delta, and how you can help to reduce their global invasion.

WHAT ARE MICROPLASTICS AND HOW DO THEY ORIGINATE?

MICROPLASTICS
Plastic particles that measure <5 mm in size.

Microplastics are little plastic pieces <5 millimeters (mm), or about 1/5 inch, in size. Depending on their origin, these plastic pieces can be

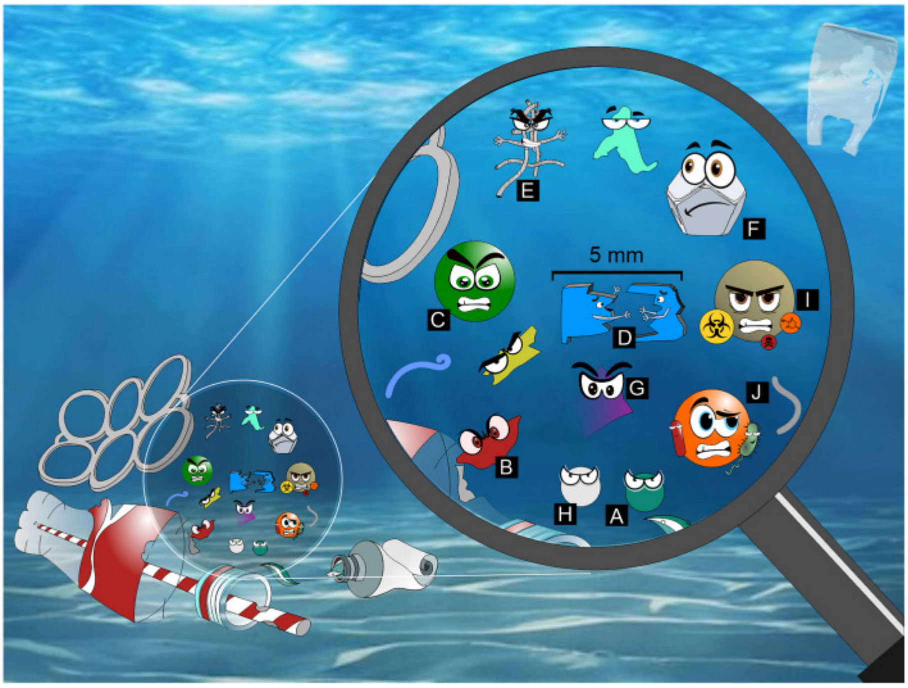

Figure 1

Figure 1

Microplastics suspended in water. Microplastics can be classified as **(A)** primary microplastics, which are created as small particles and used to create larger plastic objects or in personal care products like toothpastes, or **(B)** secondary microplastics, which result from the breakdown of larger plastic objects, such as a plastic bottle. Microplastics can exist as **(C)** pellets, **(D)** fragments, **(E)** fibers, **(F)** foams, **(G)** films, or **(H)** granules. Some microplastics can act as fomites, transporting **(I)** hazardous chemicals, or **(J)** pathogens.

PRIMARY MICROPLASTICS

Microplastics originally manufactured as tiny particles for industrial use such as microbeads in personal care products, or microfibers in synthetic textiles.

SECONDARY MICROPLASTICS

Microplastics formed overtime from the breakdown of large plastic pieces in the environment.

FOMITES

Inanimate objects that transport disease-causing pathogens such as viruses and bacteria.

PATHOGENS

Tiny agents of disease, such as viruses, bacteria, and parasites.

considered primary or secondary microplastics. **Primary microplastics** are originally manufactured as this tiny size for industrial use. For example, plastic microbeads are used in personal care products, like toothpastes and skin creams. **Secondary microplastics** originate from the fragmentation of larger plastic materials, such as plastic bottles, bags, straws, and containers, which break down in the environment over time to become microplastics (Figures 1A,B).

When classified by their visual appearance, microplastics can be pellets, fragments, fibers, foams, films, or granules (Figures 1C–H). Pellets are manufactured as little spheres to produce bigger plastic items, whereas fragments originate from plastic bottles or other plastic items that break down over time. Fibers typically come from synthetic clothes, while foam usually comes from single-use Styrofoam containers. Films enter the environment from plastic bags or food packaging, and granules come from personal care products like toothpaste. Pellets and granules are both are round, but pellets are much larger.

WHY ARE MICROPLASTICS A CONCERN?

Microplastics are a growing environmental concern because they can act as **fomites** for chemicals and disease-causing organisms called **pathogens** (Figures 1I,J) [1, 2]. This means that dangerous chemicals and harmful germs can use microplastics to hitchhike through the environment. Microplastics are also a concern because they are so

ZOOPLANKTON

Small, animal-like organisms that inhabit aquatic environments.

tiny and often look like food, so they can be eaten by aquatic and marine animals of all sizes. **Zooplankton**, little organisms living in aquatic environments that mainly eat tiny algae, will eat less food after ingesting microplastics [3]. Microplastics can become entangled within the zooplankton gut and lead to starvation, a state in which the animal no longer gets enough energy from food to survive. On a much larger scale, whales that eat massive amounts of plankton end up filtering out and consuming these microplastics, some of which carry toxic chemicals. Both the microplastics and the chemicals can accumulate in their bodies [4]. Thus, microplastics have multiple ways of harming the health of many marine animal species.

WHERE ARE MICROPLASTICS AND HOW CAN THEY AFFECT THE SACRAMENTO-SAN JOAQUIN DELTA?

ECOSYSTEM

A system of interactions between living organisms and their environment.

BIOTA

The living organisms (plants and animals) of a specific ecosystem.

Microplastics are everywhere around the world! They have made it into all the environmental compartments of an **ecosystem**: air, soil, water, and **biota** (living organisms) (Figure 2). For instance, synthetic microfibers (manmade fibers that come primarily from clothing) have been found in water, on beaches, and even in air [5, 6]. A study in the San Francisco Bay found that there are more than 1 million microplastic particles per square mile of surface water [5]. This is the same as finding over 300 microplastic pieces on a credit card-sized area! Moreover, microplastics (consisting mainly of microfibers) were found everywhere across California beaches, from Marin County in the San Francisco Bay to more than 560 miles away in San Diego, the southernmost county in California [6]. Biota of the San Francisco Bay can contain and generate microplastics, too. Pacific mole crabs and mussels accumulate microplastics in their bodies, while other marine crustaceans can generate microplastics by digging in big blocks of foam [6–8].

The Sacramento-San Joaquin Delta is a unique ecosystem where freshwater mixes with seawater, generating conditions that support diverse animal, plant, and insect species. Furthermore, the Delta serves as an important source of drinking water and agriculture for millions of people in California. The conservation of this valuable ecosystem is everyone's responsibility. San Francisco Bay area is to the west of the Sacramento-San Joaquin Delta. Higher concentrations of microplastics have been found in the San Francisco Bay waters than in the waters around other urban areas of the United States [5], and further studies are currently in progress in the Delta. Microplastic contamination in the Delta appears inevitable. There is also contamination from pesticides and other environmental contaminants that can combine to affect the health of the organisms living there. Around the world, microplastics have been found in drinking water (see **Video**) and fish. However, are there microplastics in California drinking water? Do people consume fish with microplastics in them? Do microplastics affect human health? These are some

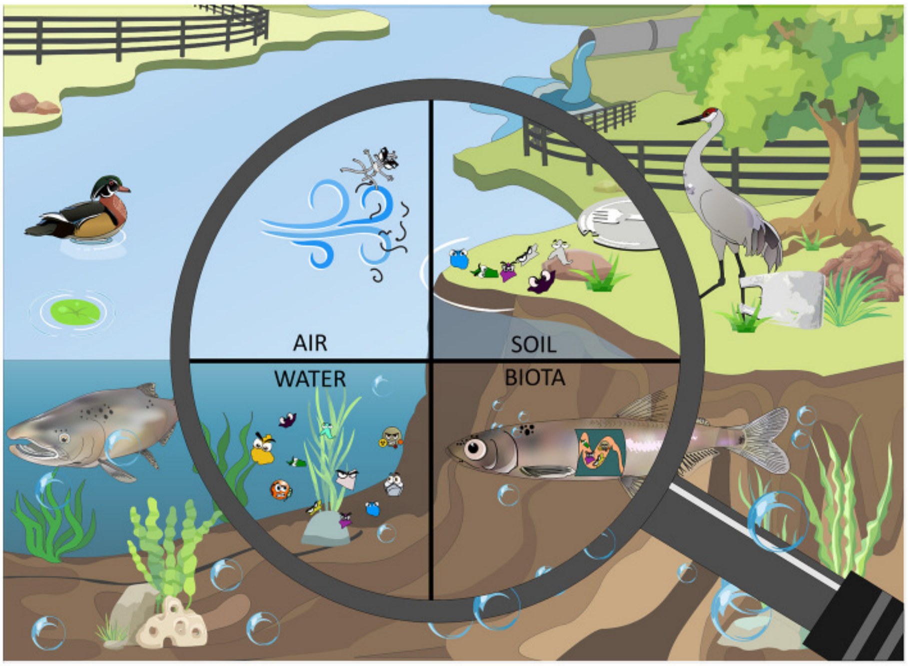

Figure 2

Microplastics in the four environmental compartments of a freshwater ecosystem: air contains floating synthetic microfibers; soil contains diverse microplastics and plastic debris; water contains suspended microplastics that interact with chemicals, bacteria, sediment, and living organisms; and biota such as fish contain microplastics in their guts.

important questions that are still unsolved in the Sacramento-San Joaquin Delta region.

WHAT CAN WE DO TO FIGHT THIS INVASION?

Did you know that, in 2017, only about 8% of plastic in the United States was recycled, and almost 27 million tons of plastic were added to landfills? As it breaks down over time, all this plastic will become secondary microplastics. Can you imagine how many tons of microplastics will be generated on Earth over the next 10 years? Remember that 27 million tons is only the plastic waste from one country in one year. Just imagine how much plastic trash we generate worldwide! This plastic overuse comes primarily from our reliance on single-use plastic products, including plastic bags, straws, plastic bottles, and foam containers.

One possible solution is to redesign the plastic industry to use new types of plastic or alternative materials that will not harm the environment. Another helpful action is to ban single-use plastics and personal-care products containing microbeads. In San Francisco, California, single-use plastic bags have been banned in grocery stores. However, these actions are not enough. Eliminating all single-use plastics will take a lot of time and effort. Many scientists are already working on alternative materials, but you can help with your own ideas, too. We invite you to brainstorm creative solutions with your science teachers and friends, by playing, experimenting, and testing.

There are other ways that you can prevent the current environmental invasion of microplastics. For example, you can avoid the unnecessary use of plastics in your daily life. Do you bring your sandwich to school in a plastic bag every day or drink water from single-use plastic bottles? Replace these with reusable containers. Do you use toothpaste with microbeads? Check the ingredients and use the internet to choose brands that do not contain microplastics. Do you use plastic straws to drink your soda? Choose a biodegradable straw or better yet, do not use one at all! You have the power to make choices that help the planet. You can also help limit the microplastic invasion by spreading the word and telling your friends and family why microplastics are a global concern. It is important that as many people as possible raise awareness of the danger that microplastics pose for our planet, and now you know enough to help with this mission!

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YOUNG REVIEWERS

CORTE MADERA SCHOOL, AGES: 10–11
We are a fifth grade class, excited about all things science. Since we live in the San Francisco Bay Area, we love to learn about the amazing wildlife and the natural environment around us.

AUTHORS

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I am a veterinarian from Peru and currently a pharmacology and toxicology Ph.D. student researcher in the Aquatic Health Program at the University of California, Davis. I have been always passionate about understanding the diseases of wild birds. My research focuses on how microplastics and their associated contaminants can harm seabirds from the Humboldt Current Ecosystem in Peru. My second passion is teaching. I developed a research volunteer program at Microplastic Fauna Peru Project for a group of young Peruvian researchers. *cmlujanvega@gmail.com

JOSÉ LUIS ORTEGA-ALFARO

I recently graduated with a bachelor's degree in biology from the Universidad Nacional Federico Villarreal in Lima, Peru. Currently, I am an ecotoxicology researcher at the Laboratory of Ecology and Animal Biodiversity and the research coordinator at Microplastic Fauna Peru Project, where I am studying the tissue distribution of microplastics in fish species from various trophic levels of the Humboldt Current Ecosystem in Peru. I would like to contribute to the understanding of toxic compound dynamics and to propose alternatives and solutions to human-made pollution.

JENNIFER COSSABOON

I am a doctoral student researcher in the Aquatic Health Program at the University of California, Davis. My fascination with wildlife health and toxicology began while working with seals and sea lions in Monterey Bay and Alaska. I am now pursuing a D.V.M/Ph.D., to pair research tools with clinical skills, so I can continue researching the role of contaminants in animal and human diseases.

SHAWN ACUÑA

Shawn Acuña is a senior resource specialist for the Metropolitan Water District of Southern California. He has almost 20 years of experience in the field of fish biology and environmental science. He has a B.S. in aquatic biology from U.C. Santa Barbara and an M.S. in animal biology and a Ph.D., in ecology from U.C. Davis. He has expertise in gross pathology, histopathology, and nutrition and health biomarkers, and has conducted field and laboratory studies on environmental stressors. He currently works on stressors and stressor effects in the San Francisco Estuary, to help keep the Estuary healthy.

SWEE J. TEH

Swee Teh, Ph.D., is the director of the Aquatic Health Program in the School of Veterinary Medicine at the University of California, Davis, and the director of the Aquatic Toxicology Laboratory; a state- certified laboratory engaged in monitoring and assessing water quality and aquatic ecosystem health. He has published over 100 research articles in peer-reviewed journals. He researches the effects and interactions of various water contaminants on aquatic organisms and ecosystems. He has been married to his wife Foo-Ching for 39 years. They have two grown children who currently live in California.

BIODIVERSITY
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CAN BACTERIA SAVE AN ESTUARY'S FOOD WEB?

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YOUNG REVIEWERS:

LICEO CLASSICO PAOLO SARPI

AGES: 15–17

Scientists in the San Francisco Estuary (Estuary) are trying to solve the puzzle of why many small native fishes are starving. Zooplankton are important food for small fish in the Estuary, but there are fewer zooplankton in the Estuary than there used to be. Why are zooplankton in such short supply? Possibly because they are hungry, too! Floating plant-like organisms called phytoplankton, the usual food for zooplankton, have disappeared from some areas of the Estuary. However, bacteria may be able to help with this food shortage. Bacteria in the water eat a carbon-containing substance called organic matter that is released from both living and dead organisms. As bacteria eat and grow, they stick together to make clumps of food big enough for zooplankton to eat. Since a lot of organic matter exists in the Estuary, these tiny bacteria may be able to save small native fishes by making food for zooplankton. In this article we will discuss what dissolved organic matter is and how bacteria may be an important puzzle piece for making fish food in the estuary.

THE SAN FRANCISCO ESTUARY FOOD WEB PUZZLE

The San Francisco Estuary (Estuary), in California, USA, is the largest estuary on the west coast of North America. The Estuary is formed by the Sacramento and San Joaquin rivers, which meet and flow westward through San Francisco Bay into the Pacific Ocean. Along the way, the fresh water from the rivers and the salty water from the ocean mix and form the San Francisco Estuary (Figure 1).

Scientists have studied the upper San Francisco Estuary since the 1960s, when the Estuary had many healthy native fish populations. In the 1980s, scientists began to notice that some native fish species were disappearing from the Estuary. They determined that many small fish were probably dying because they were running out of food. Like putting together a jigsaw puzzle, scientists pieced together the **food web** of the Estuary to understand what is needed to make these fishes healthy.

FOOD WEB

The map of "who eats whom" in an area. Food web maps help scientists describe connections between organisms and identify critical food pathways that need to be studied.

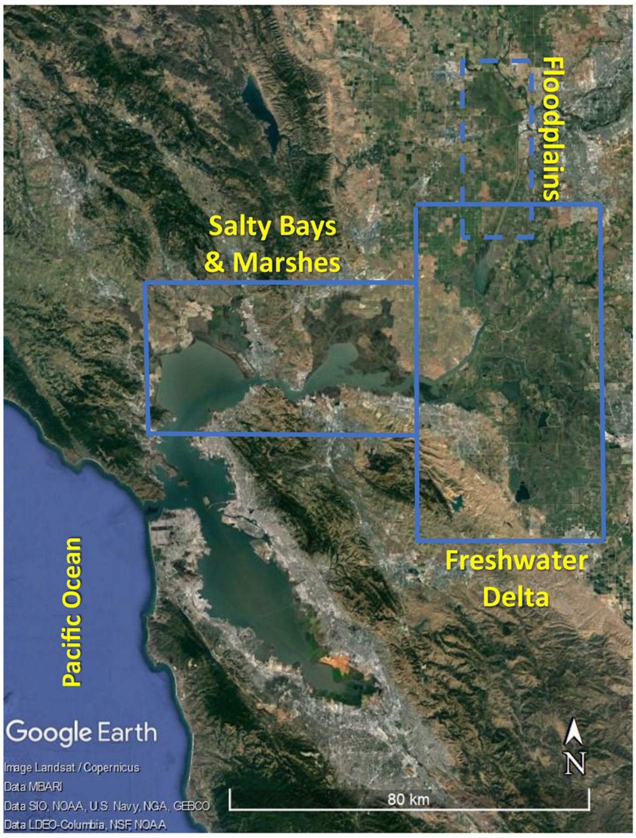

Figure 1

Figure 1

The upper San Francisco Estuary (boxed areas) showing its many ecosystems. The Estuary contains salty marine bays that form slightly salty marshes, freshwater rivers that meet to form a delta, and floodplains, which are lands that flood when river flow is high.

CARBON

An element that is used to build organic matter. Carbon is considered the "building block of life."

ORGANIC MATTER

Carbon-containing matter from living organisms or recently living organism. Organic matter can be particulate (large enough for animals to eat) or dissolved (so small that only bacteria can eat it).

PHYTOPLANKTON

Microscopic, single-celled or colonial plant-like organisms that float in the water.

ZOOPLANKTON

Tiny organisms in the water that eat phytoplankton and other small organisms. Zooplankton are an excellent food for small fishes.

BACTERIVORES

Microscopic, single-celled organisms that use bacteria as a source of food. Bacterivores can be eaten by zooplankton, so they directly connect bacteria to the larger animals of the food web.

MICROBIAL LOOP

The process by which carbon from dissolved organic matter is transferred into the food web with the help of bacteria and bacterivores.

WHAT IS ORGANIC MATTER?

Have you ever heard the statement, "carbon is the building block of life"? That is because all living beings are made of **carbon**. Carbon is a very special element that easily combines with other elements to form what is called **organic matter**.

There are two types of organic matter: particulate and dissolved. Particulate organic matter includes plants and animals and is big enough for animals to see and eat. In the waters of the Estuary, particulate organic matter includes tiny floating plant-like organisms called **phytoplankton** and tiny animals called **zooplankton**. When you swim in the Estuary, you are an example of a large piece of particulate organic matter in the water!

The Estuary also contains carbon in the form of dissolved organic matter. This is organic matter in liquid form. Dissolved organic matter is too small for us to see and for animals to eat. It comes from dead plants and animals that release liquids as they decay. Dissolved organic matter also comes from living organisms that leak fluids. For example, phytoplankton cells leak fluids through their cell walls, and zooplankton release liquid waste.

WHERE DO BACTERIA FIT INTO THE FOOD WEB PUZZLE?

Bacteria are the only critters that can eat dissolved organic matter! As bacteria eat and grow, they stick together and form small clumps. These clumps of bacteria eventually become big enough as particular organic matter and can be eaten by small animals. Small clumps of bacteria are often eaten by organisms called "**bacterivores**," which can then be eaten by zooplankton. If the clumps of bacteria get really big, they can also be directly eaten by zooplankton.

The process that converts dissolved organic matter to particulate organic matter through the growth of bacteria is called the **microbial loop** (Figure 2). Without this highly important process, the carbon that is present in dissolved organic matter would be "lost" to the food web [1]!

THE UPPER SAN FRANCISCO ESTUARY IS LOW IN PARTICULATE ORGANIC MATTER

Particulate organic matter in the form of phytoplankton is the main food that supports the food web in the Estuary [2]. However, compared to most other estuaries, the upper San Francisco Estuary is low in particulate organic matter. Most of the organic matter in the Estuary is

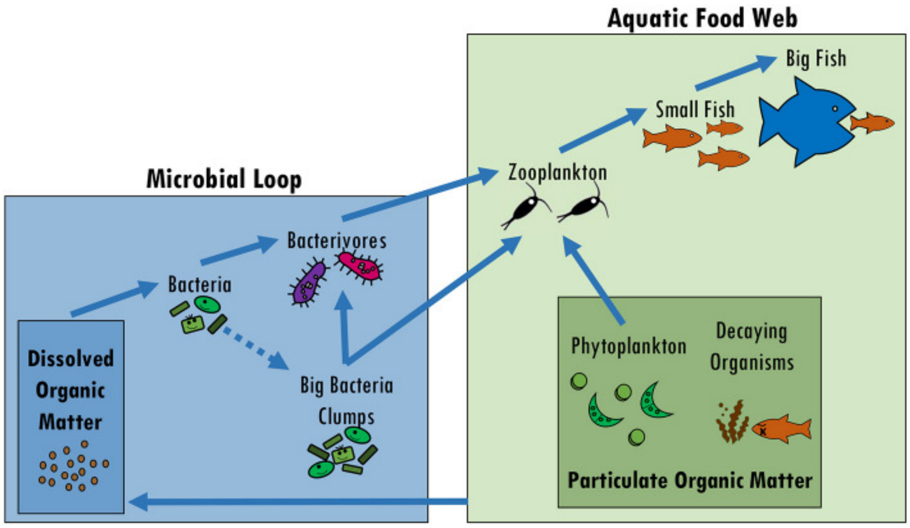

Figure 2

The link between the microbial loop and the aquatic food web in the San Francisco Estuary. Dissolved organic matter becomes particulate organic matter as bacteria eat it and grow to form clumps. Small clumps of organic matter are eaten by bacterivores and zooplankton eat both bacterivores and big clumps of organic matter. Zooplankton are then eaten by fish. Dissolved organic matter is leaked or excreted by zooplankton and fish, and the cycle, called the microbial loop, starts over. Blue arrows show the movement of organic matter from the microbial loop to the food web and back.

dissolved organic matter, which can only be taken up in the microbial loop [2].

Scientists have two explanations for the low amount of particulate organic matter in the Estuary. Firstly, there are not enough phytoplankton to support the food web. Even though the Estuary has plenty of nutrients for phytoplankton to eat and grow, they still grow slowly in the Estuary because the water is so muddy that it blocks light from entering the water. Without light, phytoplankton cannot grow fast enough to feed zooplankton [3]. Second, an invasive clam species, the overbite clam, entered the Estuary in 1986 [3, 4]. This clam filters phytoplankton out of the water for its food, which lowered the amount of phytoplankton available for zooplankton between the 1970's (Figure 3A) and the 1980's (Figure 3B). Between the muddy water and the invasive clams, not enough phytoplankton exists anymore to feed zooplankton in many parts of the Estuary.

CAN BACTERIA SAVE THE FOOD WEB?

Initially, the microbial loop was thought to be unimportant to the food web in the upper Estuary [2]. However, recent research suggests the type of zooplankton in the food web have changed, and new species are more able to use bacteria as food. A new species of small zooplankton called *Limnoithona* is now very common in the Estuary [5]. *Limnoithona* may be thriving because it can eat the tiny bacterivores and clumps of bacteria produced by the microbial loop! However, scientists are not sure whether *Limnoithona* will be good food for small fish in the Estuary.

In a study conducted in the floodplains, researchers found that zooplankton grew well when decaying organic matter was present in

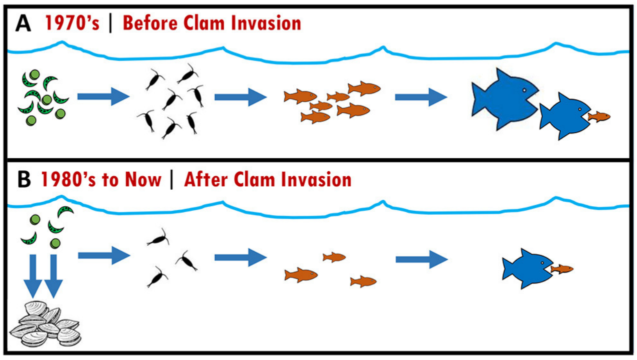

Figure 3

Figure 3

Invasion by the overbite clam changed the food web in the San Francisco Estuary. The arrows show "who eats whom" in the Estuary. **(A)** Before the invasion of the overbite clam, the zooplankton ate phytoplankton. Small native fishes were abundant because they had lots of zooplankton to eat. **(B)** After the overbite clam arrived, phytoplankton decreased because the overbite clam ate them. This means there was less food for zooplankton which affected food for fish.

the water [6]. This decaying organic matter helped grow 53 times more zooplankton compared to those in the nearby river. In fact, young fish in the floodplain had so much zooplankton to eat that they grew five times faster than fish in the river! The ability for the floodplain to grow a lot of fish food, possibly by using the microbial loop, may be a new and key piece to the food web puzzle.

SOLVING THE PUZZLE TO BRING FISH FOOD BACK

We hope that future studies will help us determine how the microbial loop can contribute to bringing fish food back to the parts of the Estuary where fish are starving. Can you think of ways that the microbial loop might be able to help small native fishes in the upper San Francisco Estuary? Maybe a small native zooplankton species can thrive on bacteria from the microbial loop and can also be a great fish food. Maybe floodplains can be flooded on purpose to create the dissolved organic matter needed to grow bacteria and feed fish [7]. Maybe it is possible to transport the fish food grown on floodplains to areas in the Estuary where food is harder for fish to find. Much work remains to be done, but scientists are hopeful that these pieces of the puzzle will fit together to help them bring fish food back to the upper Estuary!

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YOUNG REVIEWERS

LICEO CLASSICO PAOLO SARPI, AGES: 15–17

We are the best school in the world, because we are the tallest and the cleverest, and we have the best teachers. But specifically we are the best class of the school because we have a lot of different type of people and we are very funny. We love science because we have a very good teacher.

AUTHORS

ALICE TUNG

I am a Ph.D., student of ecology at the University of California—Davis. I study how well-phytoplankton grow in the upper San Francisco Estuary. I am especially interested in researching how salty wetlands that are managed for duck food in Suisun Marsh may also contribute to fish food. On my free time, I love making desserts—dark chocolate mousse and French macarons are my specialty! *amatung@ucdavis.edu

PEGGY W. LEHMAN

I am a Ph.D., ecologist with a specialty in phytoplankton and currently work as a senior scientist for the State of California, USA. My research includes the growth, causes, and ecosystem impacts of the cyanobacterium *Microcystis* which forms toxic blooms in the freshwater reaches of San Francisco Estuary. I also study the phytoplankton in rivers and wetlands within the Estuary in response to environmental conditions, including climate change. In my free time, I enjoy watching changes in phytoplankton blooms as I kayak through rivers and lakes near home. *Peggy.Lehman@water.ca.gov. To find out more about my work see orcid.org/0000-0001-9556-0542.

JOHN DURAND

I study the ecology of food webs and fish in estuaries. I am particularly interested in how restored and managed wetlands create food and habitat for fishes and other animals, and the effects of climate change on these habitats. I got interested in wetlands and estuaries because I spent a lot of time kayaking in them, and I had a lot of questions that eventually led me to get a Ph.D., in ecology at the University of California, Davis, where I still work as a research scientist.

frontiers FOR YOUNG MINDS

THE EARTH AND ITS RESOURCES
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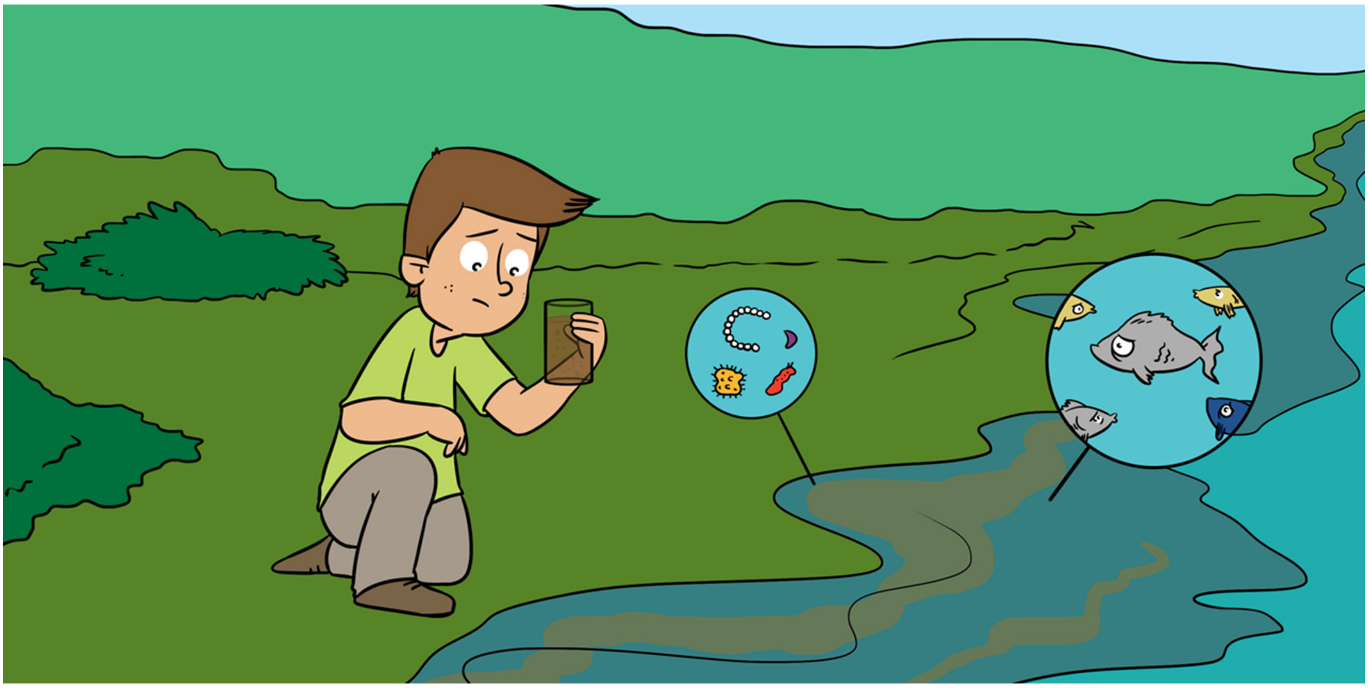

POWERING LIFE IN THE WATER: PHYTOPLANKTON IN THE SAN FRANCISCO ESTUARY

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YOUNG REVIEWERS

SCUOLA EUROPEA DI VARESE

AGES: 11-12

Phytoplankton are probably the most important aquatic organisms that you have *NEVER* seen! Phytoplankton are nearly invisible and use sunlight, carbon dioxide, and nutrients in water to produce sugars that power the estuary food web. The amount of phytoplankton growth is important because phytoplankton are the food for aquatic animals like zooplankton and fish. Scientists working in the San Francisco Estuary are concerned because phytoplankton growth is low, and some animals are starved for food. Measuring phytoplankton growth is hard because growth is low and the conditions in the water that control growth change quickly. As a result, scientists created a mathematical equation, called a model, that brings together the number of phytoplankton available to grow, the amount of sunlight, and the muddiness of the water to estimate phytoplankton growth each day. This way, scientists can determine where and when food is available to power life in the San Francisco Estuary.

WHY ARE PHYTOPLANKTON IMPORTANT TO ESTUARIES?

Phytoplankton (also called algae) are probably the most important aquatic organisms that you have *NEVER* seen! That is because most phytoplankton are so small you cannot see them with your eyes. You would need to line up between 5 and 100 phytoplankton to equal the width of a human hair! Phytoplankton are plant-like (phyto) organisms that float (plankton) in the water. They are important because they are like tiny sugar-making factories that use raw materials around them to make food for animals in the **estuary**. The process they use to make this food is called **photosynthesis**. Photosynthesis uses carbon dioxide gas and nutrients, along with sunlight, to make sugary food that powers all the animal life found in the San Francisco Estuary.

ESTUARY

A place where the river meets the ocean water as it moves inland along rivers due to the tide. Tides are the daily rise and fall of ocean water due to the attraction of the moon and sun.

PHOTOSYNTHESIS

A process used by plants, algae, and some bacteria, which uses the Sun's energy and carbon dioxide gas from the air to make sugars they can use for growth.

Phytoplankton have many beautiful shapes and have amazing features that help them live in an estuary. They can look like a necklace, crescent moon, or even stars. Diatoms have a hard outer "shell" made from silica, the same material as glass (Figures 1A,C,D). Their glass shells make them strong enough to withstand the action of wind and waves. Diatoms make an oil to help these heavy shells float. Because oil is lighter than water and does not mix with water, diatoms float rather than sink. Other phytoplankton called green algae are the most plant-like (Figures 1B,E,F). They are often round balls or string-like, and they are bright green due to an abundance of a pigment called **chlorophyll-a** that absorbs sunlight. All the plants on earth today developed from green algae. Cyanobacteria are a type of bacteria that contain a greenish-blue pigment called cyan (Figures 1G,H). Like phytoplankton, they also use photosynthesis to produce sugars for the food web. Cyanobacteria were the first organisms on Earth to use photosynthesis, more than 3 billion years ago! Dinoflagellates come in many shapes, are often yellow or reddish in color, and are sometimes encased in a plate-like armor (Figure 1I). Two whip-like tails allow dinoflagellates to swim rapidly in many directions. Although many dinoflagellates use photosynthesis to produce sugars, they can also eat other small plankton.

CHLOROPHYLL-*A*

A green pigment in plants and phytoplankton that captures the energy of the Sun for photosynthesis.

Phytoplankton grow well in estuaries where water is trapped within warm, shallow areas and sunlight, carbon dioxide, and other nutrients needed for growth are plentiful. Phytoplankton nourish many animals in the estuarine food web, including fish. In fact, estuaries are often referred to as "nurseries" for young fish because of the abundant food available for their growth. Some phytoplankton are more nutritious than others, so fishery scientists and people who fish want to understand how to grow more of the nutritious phytoplankton, so they can grow more fish.

Scientists are worried about phytoplankton in the San Francisco Estuary because, compared to many other estuaries, phytoplankton do not grow well there [1]. One major reason for low phytoplankton

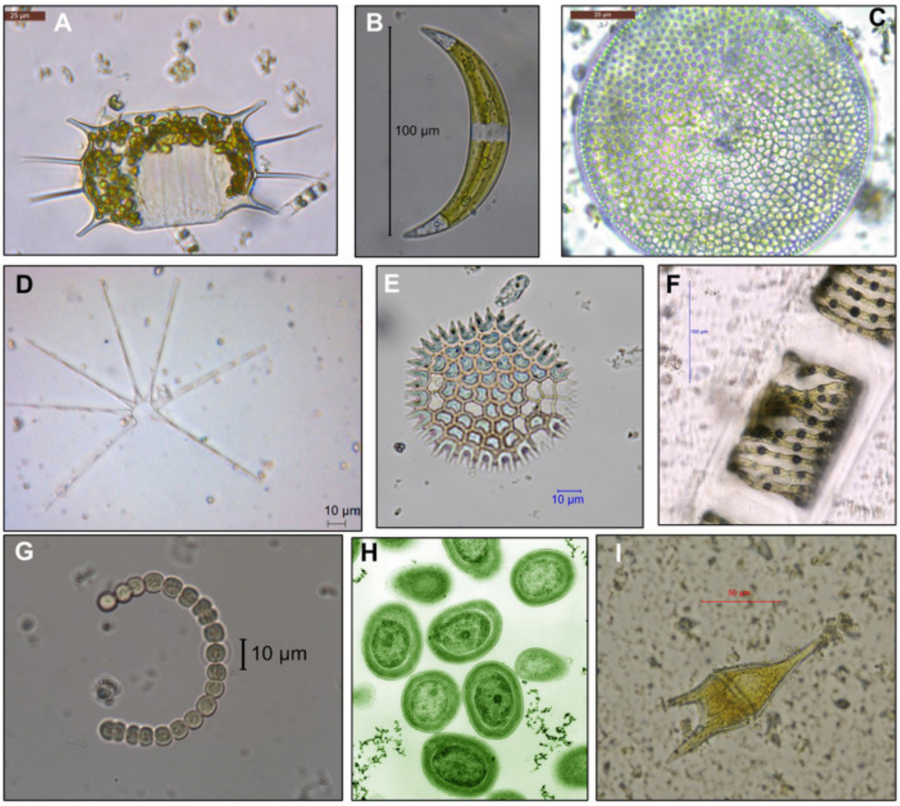

Figure 1

Figure 1

Examples of estuarine phytoplankton, including diatoms **(A,C,D)**, green algae **(B,E,F)**, cyanobacteria **(G,H)**, and dinoflagellates **(I)**: **(A)** *Odontella* sp., **(B)** *Closterium* sp., **(C)** *Coscinodiscus* sp., **(D)** *Asterionella* sp., **(E)** *Pediastrum boryanum*, **(F)** *Spirogyra maxima*, **(G)** *Anabaena* sp., **(H)** *Prochlorococcus*, **(I)** *Ceratium furca.* Scale bars are microns (µm). One micrometer equals one millionth of a meter [Image credits: All images except for **(E)** were provided by the California Department of Water Resources (T. Brown). Image **(E)** was produced by E. Barry H.F. Luke Thompson from Chisholm Lab and Nikki Watson from Whitehead, MIT, CC0 and obtained from Wikimedia Commons Rosen, Public domain, via Wikimedia Commons].

growth is that the Estuary has very muddy water, which blocks the sunlight needed for photosynthesis. Phytoplankton growth in the Estuary is barely fast enough to keep up with the number of phytoplankton being eaten by animals, and some animals in the estuary appear to be starved for food. This may help to explain why some Estuary fish are near extinction [2, 3].

PHYTOPLANKTON GROWTH IS HARD TO MEASURE!

It is difficult to measure the growth of phytoplankton in the Estuary because they are so small. Instead, scientists estimate growth by measuring the conditions that help phytoplankton to grow. These conditions include the number of phytoplankton available to grow, the amount of sunlight in the sky, and how clear the water is. But each of these conditions changes throughout the day, the season, and the year! To solve this problem, scientists use a mathematical equation, called a **model**, to describe and explain what happens to phytoplankton even in changing conditions [4, 5] (Figure 2). The model predicts that there will be high phytoplankton growth on days when there are many phytoplankton around to grow, when the sun is bright, and when the water is clear and not muddy. If any of these conditions are less than ideal, phytoplankton growth will be decreased. Using the

MODEL

A way of using math to describe processes in nature as simply as possible.

Figure 2

Figure 2

Scientists use a mathematical model to predict phytoplankton growth. The number of phytoplankton available to grow is estimated by the concentration of chlorophyll-*a*, measured a using fluorometer. Sunlight is measured using radiometer and the clearness of the water by turbidity meter. This model predicts that phytoplankton growth will be high when the number of phytoplankton available to grow is high, the amount of sunlight in the sky is high, and the clearness of the water is high.

FLUOROMETER

A scientific instrument used to measure the amount of light produced from a material.

RADIOMETER

A scientific instrument used to measure the amount of energy from the Sun.

model, scientists can estimate phytoplankton growth in the estuary without ever touching the water!

MEASURING PHYTOPLANKTON

Because phytoplankton are so tiny, it can be very difficult to count them. Instead, scientists estimate the number of phytoplankton by measuring the concentration of the green pigment, chlorophyll-*a*, that all phytoplankton use to absorb the sunlight needed for photosynthesis. An instrument called a **fluorometer** is used to continuously measure the concentration of chlorophyll-*a* in the waters of the San Francisco Estuary. There is more chlorophyll-*a* during the warm summer months when sunlight is high (Figure 3A). The amount of chlorophyll-*a* present each day also depends on how many phytoplankton were eaten by animals, such as zooplankton and clams during the previous day.

MEASURING SUNLIGHT

The amount of sunlight in the sky changes depending on where we are on the Earth. Near the Earth's equator, sunlight is strong year-round. In contrast, near the Earth's poles, the sunlight is relatively weak. Because the San Francisco Estuary is located between the equator and the North Pole, it receives an intermediate amount of sunlight that is greatest in June and July (Figure 3B). The amount of sunlight hitting the water varies each day, depending on how cloudy or clear the sky is and on the amount of fog that enters the Estuary from the nearby ocean. Instruments called **radiometers** are used to measure the amount of sunlight that reaches the surface of the water.

SEDIMENT, PHYTOPLANKTON'S SUNBLOCK

Once sunlight reaches the surface of the water, it must pass through the water to reach the phytoplankton. Here is where things become difficult for phytoplankton in the San Francisco Estuary, because the Estuary's waters have a lot of sediment (very fine sand and mud) that makes them muddy. Muddy water blocks sunlight from entering below the surface of the water where phytoplankton can use it. The Sierra Nevada mountains, located 300 km east of San Francisco Estuary, are

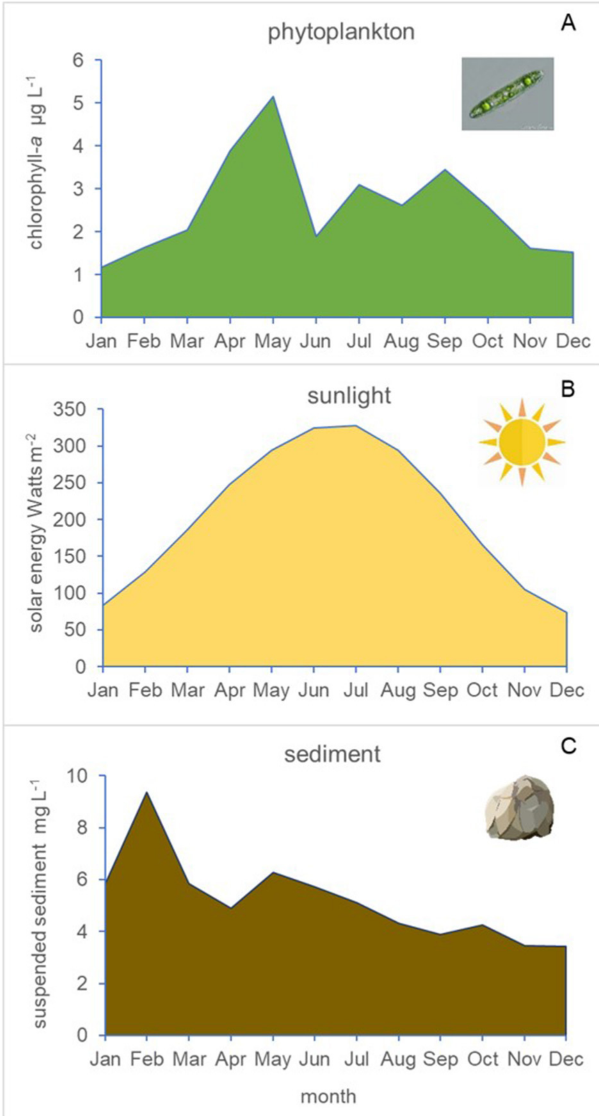

Figure 3

Figure 3

(A) Phytoplankton mostly grow in the spring and summer, so measurements of chlorophyll-*a* are highest then. However, phytoplankton are also eaten by zooplankton and clams in the summer, which decreases the amount of chlorophyll-*a*. **(B)** The amount of sunlight increases in the spring, peaks in June/July and then decreases. **(C)** Sediment in the water increases during the rainy season in winter and spring, as rivers carry bits of rock and sand from the mountains into the Estuary.

a major source of the sediment. Rainwater, ice, and snow break down the mountain rock, which is carried by rivers into the Estuary. Most of the rain falls between November and April, so it is not surprising that sediment is high in the water during the winter and spring (Figure 3C). Some of the sediment in the estuary today is the result of gold mining that occurred between 1848 and the mid-1850s, during the California Gold Rush!

Muddy water is also caused by sediment that sits on the bottom of the rivers and gets stirred up by winds and tides. This is particularly important for the San Francisco Estuary, which is one of the windiest estuaries in the world and has a large tide. Ocean tides move water into and out of the estuary twice each day. So, the winds and tide act like a spoon in a glass filled with water, stirring everything up and keeping the sediment in the water, where it can block the sunlight needed by phytoplankton. Muddiness from sediment in the water can be measured with a **turbidity meter**.

TURBIDITY METER

A scientific instrument used to measure how much light moves through water.

HOW DO PREDICTIONS OF PHYTOPLANKTON GROWTH HELP THE SAN FRANCISCO ESTUARY?

Based on the number of phytoplankton, the amount of sunlight, and the muddiness of the water—only measured in a few locations—scientists use models to estimate the growth of phytoplankton throughout the Estuary. Scientists use these estimates of phytoplankton growth to find ways to increase the amount of food for fish in the Estuary. Scientists also use estimates of phytoplankton growth to understand why fish populations change over time and how they are affected by different kinds of phytoplankton food.

Conditions in the San Francisco Estuary are changing [5]. These changes may include the growth of toxic phytoplankton, also called harmful algae [6] that are increasing with global warming and pollution. These changes may create more problems for animals that live in the estuary. Our research may help us understand how to reduce harmful phytoplankton and encourage the growth of phytoplankton that will feed estuarine animals. Whatever happens, we know that phytoplankton will continue to be among the most important aquatic organisms that you will *NEVER* see!

ACKNOWLEDGMENTS

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YOUNG REVIEWERS

SCUOLA EUROPEA DI VARESE, AGES: 11-12

These young, very international and a little crazy scientists love to discover the world around them! They are a great team and managed to collaborate successfully with each other on their first scientific manuscripts!

AUTHORS

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I am an associate professor of oceanography at the California State University Maritime Academy. My research interest is marine microbial biogeochemistry. I am especially interested in understanding how nutrients shape marine ecosystems. I work in diverse environments including the Arctic and Antarctic, coastal upwelling systems, the equatorial ocean, and estuaries. A native of the US east coast, I have conducted estuarine research in the Delaware and Chesapeake Estuaries

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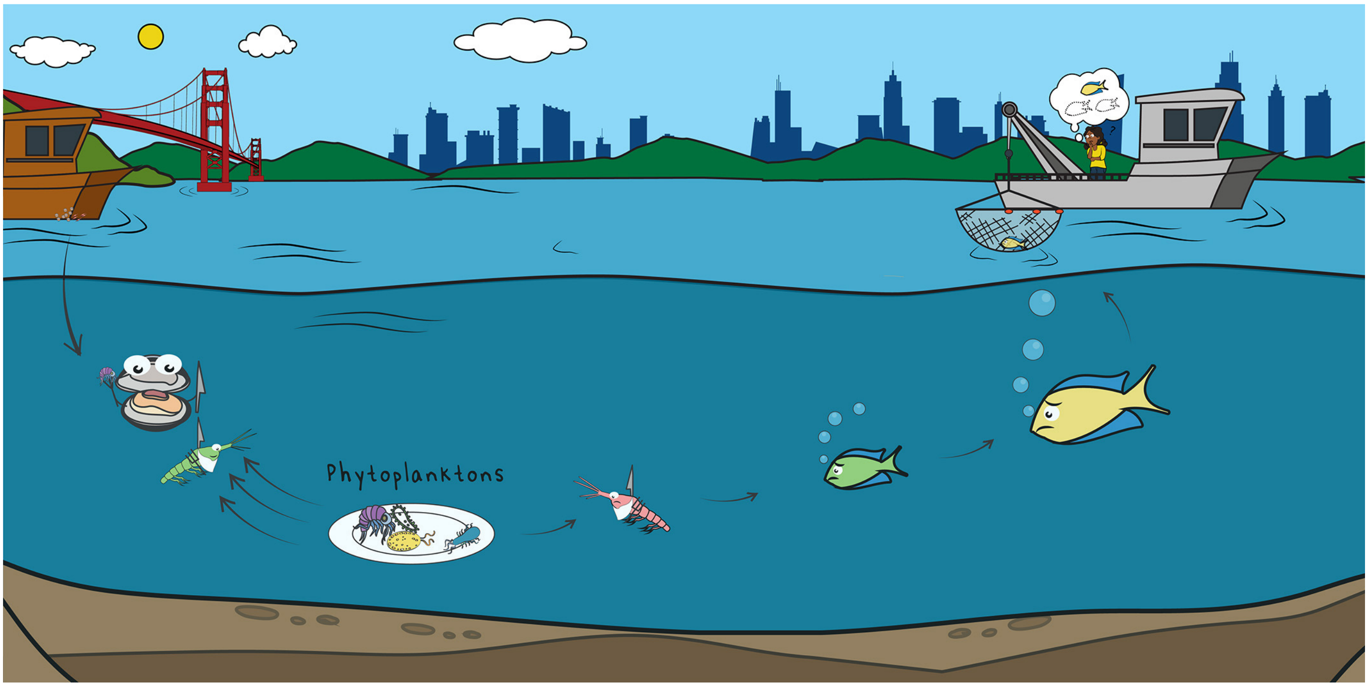

THE SMALLEST ANIMALS IN THE WATER: TINY BUT MIGHTY

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YOUNG REVIEWERS:


CHERYL
AGE: 9


PRICE
AGE: 13


PROVIDENCE
AGE: 10

Zooplankton are the smallest animals in the water. They feed on small floating plants and are food for fish. In some places, zooplankton have been studied for over 50 years because they give scientists information about water quality. In the San Francisco Estuary, many zooplankton species from far away came hitch-hiking on ships, settled, multiplied, and reduced native zooplankton. Then, the number of zooplankton dropped by half because a hitch-hiking clam ate all phytoplankton. These dramatic changes did not leave much food for fish, which also began to drop in number in the Estuary. Thus, changes that occur with the smallest plants and animals in the water can reach all the way to the top of the food chain, and can even affect humans.

THE SMALLEST ANIMALS IN THE WATER

ESTUARY

A water body where the river meets the ocean. Here freshwater from the river mixes with salty ocean water.

ZOOPLANKTON

Tiny animals that live in the water. Some resemble miniature shrimp, crabs, or snails, and you need a magnifying lens to see them properly.

PROTOZOANS

A group of tiny organisms that consist only of one single cell.

Waters like oceans, lakes, and estuaries contain millions of small animals called **zooplankton**. These animals are so small that most can only be seen with a microscope (Figure 1A). Zooplankton range in size from the diameter of a hair to the diameter of a big tree. If you have ever looked at a drop of water under a microscope and seen small animals swimming around, then you have seen zooplankton. The smallest zooplankton are only made of one cell and are called **protozoans**. They can be as small as 20 micrometers (μm), which means that they can be 50 times smaller than a millimeter [2]. Most zooplankton species with multiple cells are bigger than 1 mm, but some are still so small that you need a microscope to see them. Jellyfish are the largest zooplankton and can be up to two meters long.

One type of zooplankton, called copepods, are particularly outstanding. They are important food for many fish and support their growth. This is of course in reality more complicated and involves many different species. For example, the copepod may eat a smaller zooplankton, called a rotifer. The rotifer eats a protozoan, which eats small phytoplankton and bacteria, and all of them get rid of waste that feed the bacteria.

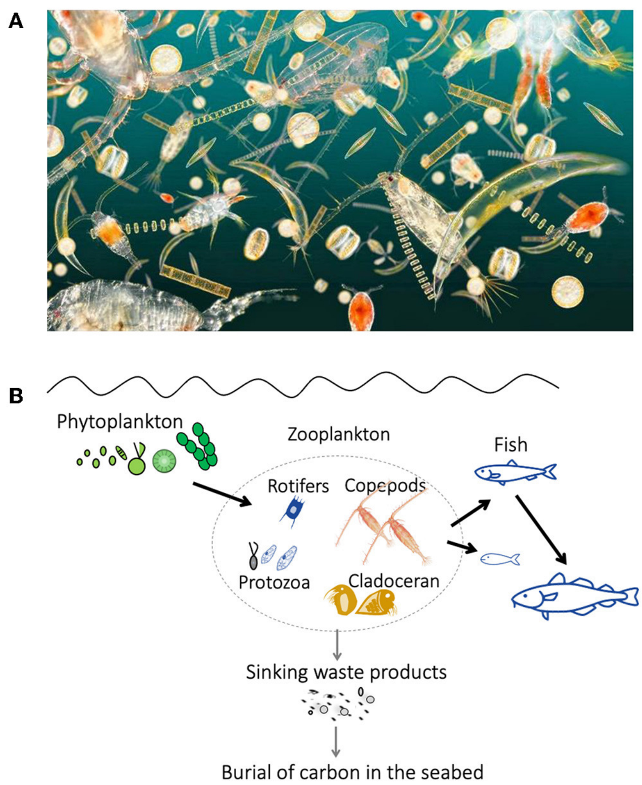

Figure 1

(A) Phytoplankton and zooplankton seen under the microscope. The small, greenish cells are phytoplankton. The larger, transparent organisms with legs and long antennae are copepod zooplankton (Source: `https://www.havet.nu`). **(B)** An aquatic food web, showing zooplankton that eat phytoplankton, and that are themselves eaten by fish. Zooplankton waste products (or poop) sink down to the sea floor, where the carbon they contain can remain buried for millions of years. Adapted from [1].

ZOOPLANKTON HELP TO KEEP BALANCE

Zooplankton are the most common animals on our planet and are an important part of the **food web**. Some zooplankton eat small floating plants, called **phytoplankton** (or algae), and some eat other zooplankton. Zooplankton themselves are then eaten by fish. One type of zooplankton, called **copepods**, are particularly outstanding. They are important food for many fish and support fish growth. When fish eat copepods or other zooplankton, this moves energy from small plants to larger animals, higher in the food chain—including animals that humans like to eat. The food chain from phytoplankton to copepods to fish is the most important flow of energy in the ocean. Of course, the story of who-eats-whom in the water is more complicated than this and contains many different species. That is why we call it a food web (Figure 1B).

Zooplankton do even more to contribute to the food web. They take up important nutrients, such as the healthy fats produced by phytoplankton, and make those nutrients available for fish. So, the healthy fats in the fish that you eat are produced by phytoplankton and carried to fish by zooplankton [3]. Zooplankton also help balance the water environment by keeping algae levels down. Without zooplankton to eat the algae, the water would be much greener and slimier. Last, zooplankton also help regulate the **carbon cycle**. Just like all animals, zooplankton must get rid of their waste in the form of poop. Zooplankton waste can be food for other creatures, or it can sink to the seafloor and bury the carbon it contains for millions of years. The sinking of poop particles helps to control carbon dioxide levels in the air, which in turn helps to control climate warming [2].

CHECKING THE HEALTH OF WATER

The types of **plankton** species found in the water tell us a lot about the health of oceans, lakes, and estuaries. For this reason, plankton have been studied since the beginning of the twentieth century. Some studies have sampled plankton in the same location every month, over many years. These data are important because they tell us how the water is changing because of damage from people living nearby, or because of climate warming. This information helps managers and scientists to make choices that will assure we have clean water to drink and play in. For example, studying zooplankton is like a health check for the water.

In the San Francisco Estuary in California, especially in Suisun Bay and the Sacramento-San Joaquin Delta, scientists have studied zooplankton every month since 1972. That gives us a dataset of almost 50 years! Zooplankton samples were collected at the same stations, from Suisun Bay upstream into the Delta, by the California Department of Fish and Wildlife. These data tell many stories of how humans have

FOOD WEB

A diagram showing how various species of animals, like phytoplankton, zooplankton, and fish, are connected to help them survive.

PHYTOPLANKTON

Tiny, microscopic organisms living in the water that get their energy from the sun, just like plants.

COPEPOD

The most numerous multicellular zooplankton and an important food source for fish.

CARBON CYCLE

The way in which carbon, the building block of life, travels from the atmosphere to plants, animals and finally stored at the seafloor or travels back to the atmosphere.

PLANKTON

Tiny plants and animals that live in the water. These include multiple functional and taxonomic groups, from viruses and bacteria to phytoplankton and zooplankton.

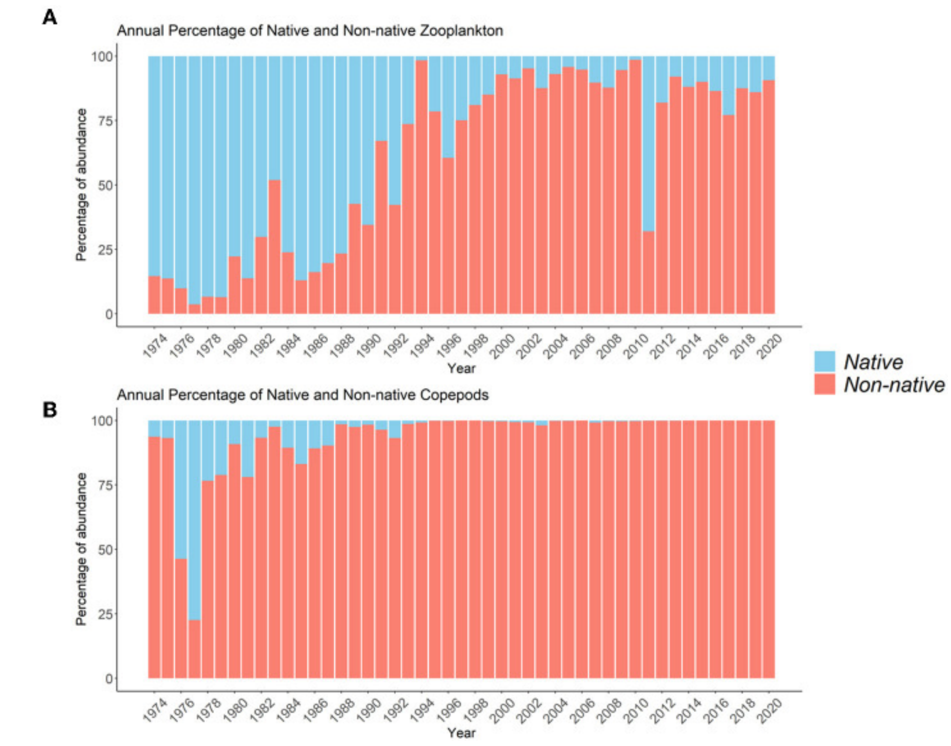

Figure 2

Figure 2

(A) The percentage of native and non-native (introduced) zooplankton and **(B)** copepods in the San Francisco Estuary from 1974 to 2017. You can see that native zooplankton, and particularly copepods where replaced by introduced species.

changed the water quality, as well as the animals and plants living in the Estuary.

HITCH-HIKERS SETTLED IN THE SAN FRANCISCO ESTUARY

Ongoing observations of the San Francisco Estuary waters tell us that many species from far away have settled and multiplied in the Estuary [4]. This occurs as more and more ships travel between countries. Many species "hitch-hike" on boats and ships and are transported between countries without humans noticing [5]. These non-native plants and animals can then establish themselves in their new environment. Because these species often have no predators in their new environment, they can become so numerous that they take over, becoming **invasive species** (Figure 2) [5]. These invasive species change the community because the native species of zooplankton can no longer find enough food to eat or space to live in, so their numbers decrease.

INVASIVE SPECIES

A species that is brought into a new ecosystem by humans and then takes over, harming native species and sometimes leading them to disappear from that ecosystem.

Over the years, changes in the San Francisco Estuary, including a decreased flow of fresh water from rivers and loss of habitats for native species, along with repeated invasions of non-native species, have made the Estuary one of the most invaded environments on the planet. After the Asian clam called *Potamocorbula amurensis* arrived in the Estuary in the late 1980s, it became so abundant and ate up so much of the phytoplankton that there was very little food left for zooplankton to feed on [6]. Fewer and fewer zooplankton were counted in water samples [7]. The total weight of all zooplankton in the Estuary dropped by more than half! Imagine losing half of your weight—that is a lot! Fewer zooplankton meant there was less food for fish in the Estuary, and the numbers of fish began to decrease too.

This is just one of many big changes that has occurred in the San Francisco Estuary. Over the last 50 years, new species have come in and pushed away many native species that used to live in the Estuary. In the saltier waters close to the ocean, large copepods and another type of zooplankton called rotifers were reduced, and instead a small copepod from Asia, called *Limnoithona*, became dominant in the water [7]. The adults can number up to 30 individuals per liter of water, and younger specimens can number up to 200 individuals per liter. This invasive copepod species is much smaller than the copepods and rotifers that used to live in these areas (Figure 2).

In the less salty part of the Estuary further upstream from the ocean, rotifers and a type of zooplankton called **cladocerans** that used to be present in high numbers were reduced when a newly arriving copepod species took over. Nowadays, cladocerans are mainly present in the upstream freshwater part (Figure 3). In addition, the numbers of certain shrimp zooplankton decreased in the entire Estuary. Some native shrimp even disappeared and were replaced by invasive shrimp species. Today, the zooplankton species that are present in high numbers in the San Francisco Estuary all came from other regions of the world.

CLADOCERA

A group of small crustacean zooplankton that is common in freshwater. The water flea is the most-studied organism of this group.

CHANGES IN ZOOPLANKTON HAVE BIG CONSEQUENCES

Newly arriving species often prefer to eat foods that are different from those eaten by the native species of the San Francisco Estuary. In upstream freshwater areas, the zooplankton used to be mainly herbivores, eating algae. But some of the newly arriving copepod species are carnivores that like to eat other zooplankton. The small copepod *Limnoithona*, which is now the most prevalent zooplankton species in the saltier part of the Estuary, prefers small animals and algae. This means that the food web in the Estuary changed dramatically over the last 50 years, due to invasive zooplankton.

With the changes in zooplankton, fish in the San Francisco Estuary now have fewer zooplankton to feed on and the zooplankton that are available are much smaller. To eat a small copepod, a fish must be able to see it, which can be hard if the copepod is too small. Fish must eat many more small copepods to fill their stomachs, which means the fish must spend much more energy to catch enough food. So, fish in the Estuary now burn more energy and get less food, which is one

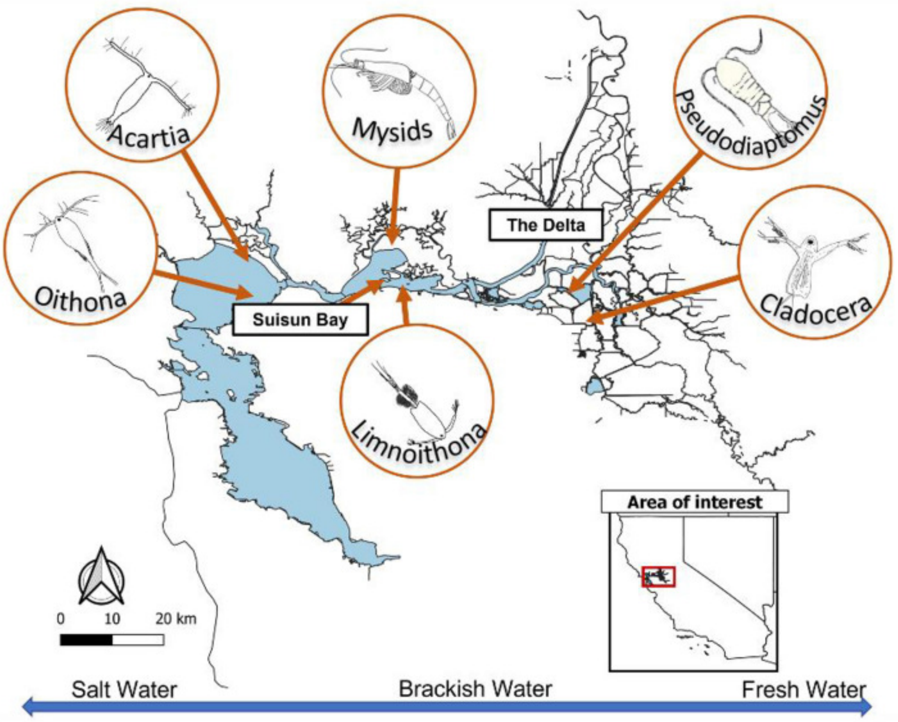

Figure 3

Figure 3

Current zooplankton species dominating in the San Francisco Estuary, from the saltier Suisun Bay to the upstream freshwater Delta.

reason why fish numbers have dropped and many fish have become smaller over the years [8].

In summary, while at first glance it might seem like changes to creatures as tiny as zooplankton should not have big consequences, when we look closer, we can see that they are tiny but mighty! Now you know that changes even in the smallest plant and animals can reach all the way to the top of the food chain. Since humans eat a lot of fish, changes to zooplankton eventually affect us, as well. That is why continued monitoring and zooplankton research are so important. We need healthy zooplankton to keep our water clean and to grow large, healthy fish that we can eat.

ORIGINAL SOURCE ARTICLE

Winder, M., and Jassby, A. D. 2011. Shifts in zooplankton community structure: implications for food web processes in the upper San Francisco estuary. *Estuar. Coasts*. 34:675–90. doi: 10.1007/s12237-010-9342-x

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YOUNG REVIEWERS

CHERYL, AGE: 9

Hi, I am Cheryl. I have a cat named Delilah and 2 little sisters called Tanya and Alice. I live in a small city of Canberra. I am sometimes pretty shy and sometimes pretty cheeky. I absolutely love icecream especially "Cookies 'n' cream." Love you all.

PRICE, AGE: 13

Price loves making up stories and has also written a book (Ms. Wasteson and the waste empire). She enjoys gymnastics, athletics, volleyball, and basketball. She is brave and bouncy. Price also enjoys quality time with family and is very creative. At her school, she is part of a "green team" that works to protect the environment. She likes debating and has a passion to study and become an activist against social injustices.

PROVIDENCE, AGE: 10

Providence is the youngest amongst her three sisters. She is playful and bouncy. Providence is curious, talkative, and likes asking many funny questions, that leaves others laughing. She loves making new friends and traveling. Providence loves science experiments. During this process, she may destroy, repair or recycle some household items. As part of this adventure, Providence repaired a spoilt speaker. But after weeks of action, she modeled the speaker wires into skipping ropes. She is passionate about music and sports including volleyball.

AUTHORS

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DELIVERING FOOD TO HUNGRY FISH IN THE SAN FRANCISCO ESTUARY

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YOUNG REVIEWERS:

DARIO
AGE: 14

VALERIE
AGE: 13

The San Francisco Estuary is home to an important endangered fish called delta smelt. Delta smelt eat small, nutritious animals called zooplankton to survive and grow. In turn, zooplankton grow by eating microscopic plant-like organisms called phytoplankton. In the past, the Estuary was full of plankton and delta smelt. Because people have removed water from the Estuary and invasive species now live there, the Estuary no longer has enough plankton to feed delta smelt, making it difficult for them to survive. Scientists have found a unique place in the Estuary, the Yolo Bypass, that has lots of fish food. The problem is that delta smelt do not live in the Yolo Bypass year-round. Scientists are working to solve this problem by sending river or farm water through the Yolo Bypass, to move fish food downstream to feed the hungry delta smelt and other fish species.

UNHEALTHY ESTUARY MEANS LESS FOOD FOR FISH

The San Francisco Estuary is home to many species of native fish and large numbers of plankton, which are tiny organisms that live in the water. Some fish species in the Estuary, such as delta smelt, are found nowhere else in the world. Plankton species that live in the Estuary include very small animals called **zooplankton**, which fish need to eat to survive, grow, and reproduce. Zooplankton eat even tinier organisms called **phytoplankton**, which are microscopic organisms that grow by harnessing energy from sunlight just like plants. This is an example of a food chain (Figure 1), and lots of crossing food chains make a **food web**. Since the 2000s, scientists have noticed that plankton have been decreasing in the Estuary, which has led to declines in the populations of several fish species [1, 2]. This is happening because the San Francisco Estuary is not as healthy as it used to be, and it all began a long time ago!

In the mid-1800s, many thousands of people rushed to California to search for gold during the Gold Rush. Since then, the San Francisco Estuary has changed a lot. People built in and around the Estuary and brought in **invasive species** (Figure 2) [3]. Since the 1950s, people have removed large amounts of water from rivers draining the Estuary, for farming and for use by people living in cities. Developing the landscape and removing water destroyed **tidal marshes** and **floodplains**, which fish and plankton need to feed, grow, and reproduce. Invasive species have made matters worse by occupying areas where native species live and competing with native species for plankton. As a result, there is less plankton to feed native fish, like the endangered delta smelt [2].

ZOOPLANKTON

Small animals that drift in the water current.

PHYTOPLANKTON

Microscopic organisms that grow by harnessing energy from sunlight just like plants.

FOOD WEB

A set of crossing food chains representing feeding relationships among organisms.

INVASIVE SPECIES

Animals and plants introduced by humans that disturb the ecosystem when the population reaches large numbers.

TIDAL MARSH

A wetland found along rivers, coasts, and estuaries that floods and drains with the movement of the tides.

FLOODPLAIN

An area of land next to a river that floods when the river is high.

WHY ARE DELTA SMELT IMPORTANT AND WHAT DO THEY EAT?

Delta smelt are small fish, about the length of a chicken egg, that exist only in certain parts of the San Francisco Estuary. They live for just 1 year, and their unique life cycle makes them especially sensitive to changes in their environment. Because of their sensitivity, delta smelt are considered indicators of **ecosystem** health, meaning that they tell us how healthy or unhealthy the San Francisco Estuary is. For example, large numbers of delta smelt in the Estuary indicate that the Estuary is healthy. In the 2000s, the number of delta smelt in the Estuary declined so much that they are now at risk of extinction [2], which tells us that something is wrong with the ecosystem. Like many other fish species in the Estuary, delta smelt eat zooplankton, which in turn eat phytoplankton. Delta smelt populations are declining in part because there is not enough plankton in the Estuary [2].

ECOSYSTEM

A community of living organisms interacting with the non-living components of their environment.

WHERE IN THE ESTUARY DO DELTA SMELT LIVE?

Delta smelt spend part of their lives in the freshwater portion of the Estuary, a place called the Sacramento-San Joaquin Delta. Before

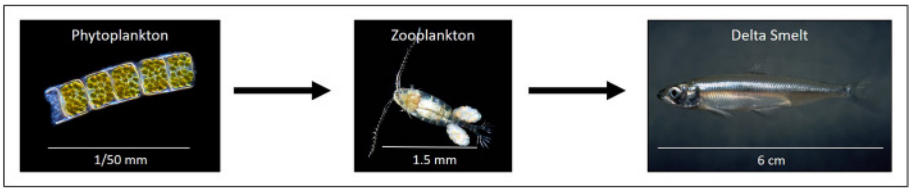

Figure 1

Figure 1

Phytoplankton are eaten by zooplankton, which are the favorite prey of the endangered delta smelt. When there are lots of phytoplankton in the San Francisco Estuary, zooplankton eat more and grow in numbers. When there are more zooplankton, delta smelt have more food to eat, which helps them to survive, grow, and reproduce. Scale bars show the length of each organism. [Photo credits: delta smelt photo by B. Moose Peterson (USFWS), zooplankton photo by Jeff Cordell (USGS), and phytoplankton photo by Alexander Klepnev (licensed under Creative Commons Attribution 4.0 International)].

humans changed the ecosystem, the Delta was a complex habitat of interconnected freshwater tidal marshes and floodplains, which is now lost. This complex habitat supported many fish and plankton species [4]. However, there are two places in the Delta, the Yolo Bypass, and the Cache Slough Complex, where freshwater still enters tidal marshes and floodplains still resemble the places where delta smelt once lived (Figure 3).

The Yolo Bypass and Cache Slough Complex together are a huge floodplain and tidal marsh, ~61 km long, with an area of 240 km^2—the same as 33,613 soccer fields! This huge place produces a lot of phytoplankton, which move downstream to the Sacramento River when water flow increases during winter and spring [5]. Because of this, the Yolo Bypass would be a good place for fish, including the delta smelt, to live [6]. However, delta smelt and other native fish cannot live in the Yolo Bypass and Cache Slough Complex during summer and fall, because the water temperature is too warm. But what if food could be moved from the Yolo Bypass and Cache Slough Complex to the places where delta smelt *do* live during summer and fall?

A FISH-FOOD FACTORY IN THE FLOODPLAIN

In 2011, scientists started monitoring the food web of the Yolo Bypass and Cache Slough Complex to learn how much phytoplankton and zooplankton exists there throughout the year and how it changes from year to year. In 2011 and 2012, there was a lot of water flowing through this huge floodplain during summer and fall. The water came from rice farms upstream of the Yolo Bypass, and it triggered an explosion of fish food in the floodplain! The water that passed through the floodplain into the Sacramento River moved lots of phytoplankton and zooplankton with it. Scientists wondered if they could move that nutritious water from the floodplain to the river in summer and fall, to feed the fish. So, with local farmers and water engineers, they developed a plan to send river or farm water through the Yolo Bypass in the summer and fall, to deliver food to hungry delta smelt and other fishes living in the Sacramento River downstream from the floodplain (Figure 3). But does this plan really work?

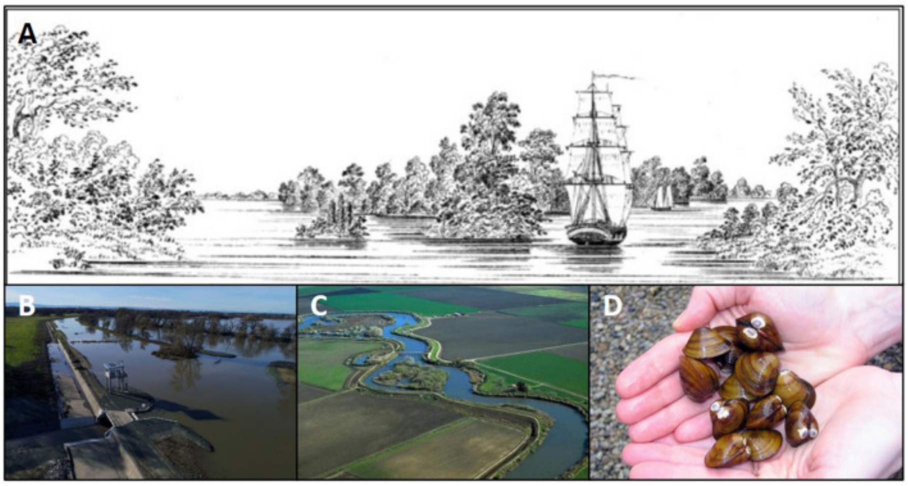

Figure 2

Figure 2

(A) Before the Gold Rush, the San Francisco Estuary had many floodplains and tidal wetlands where fish and plankton lived. **(B,C)** Since the Gold Rush, people have developed the Estuary for their own use, by building channels and weirs for flood control and water delivery to cities and farms. **(D)** People have also brought in invasive species, like the freshwater clam *Corbicula fluminea*, which occupy the Estuary and eat plankton (Image credits: drawing of estuary from Sacramento Archives & Museum Collection Center, Eleanor McClatchy Collection 1982/004/0100. Freshwater clam, Center for Lakes and Reservoirs, Flickr, Creative commons license. Photos of farmland and weir from California Department of Water Resources).

DELIVERING FISH FOOD TO DELTA SMELT

Scientists worked with water engineers to test their food-delivery plan in 2016, 2018, and 2019. Engineers used a system of pumps, canals, and weirs to move large amounts of water into the floodplain, while scientists studied the water quality and the amounts of phytoplankton and zooplankton that grew in the floodplain and downstream in the Sacramento River. In 2016, river water moved through this system, from upstream of the Yolo Bypass through the floodplain, during the summer. In 2018 and 2019, water moved from rice fields into the Yolo Bypass during the rice harvest season in summer and fall.

From this three-year study, scientists found that the food-delivery plan, which they called the North Delta Flow Action, was successful in delivering plankton from the Yolo Bypass and Cache Slough Complex to the fish living downstream in the Sacramento River. The 2016 food delivery was especially successful, because it resulted in growth of phytoplankton downstream in the lower Sacramento River, including a type of phytoplankton called diatoms, which are very nutritious for zooplankton. More zooplankton were also found downstream from the floodplain, precisely where the delta smelt like to live during the summer and fall. In 2018 and 2019, the food-delivery system was less efficient than in 2016, meaning that less food was delivered during summer and fall. However, there was still more fish food in the lower Yolo Bypass and Cache Slough Complex than before the food-delivery system was implemented.

THE FUTURE OF A SUCCESSFUL FISH FOOD-DELIVERY SYSTEM

Scientists are still studying the effects of the North Delta Flow Action, and they plan to continue it for many more years. Producing food in

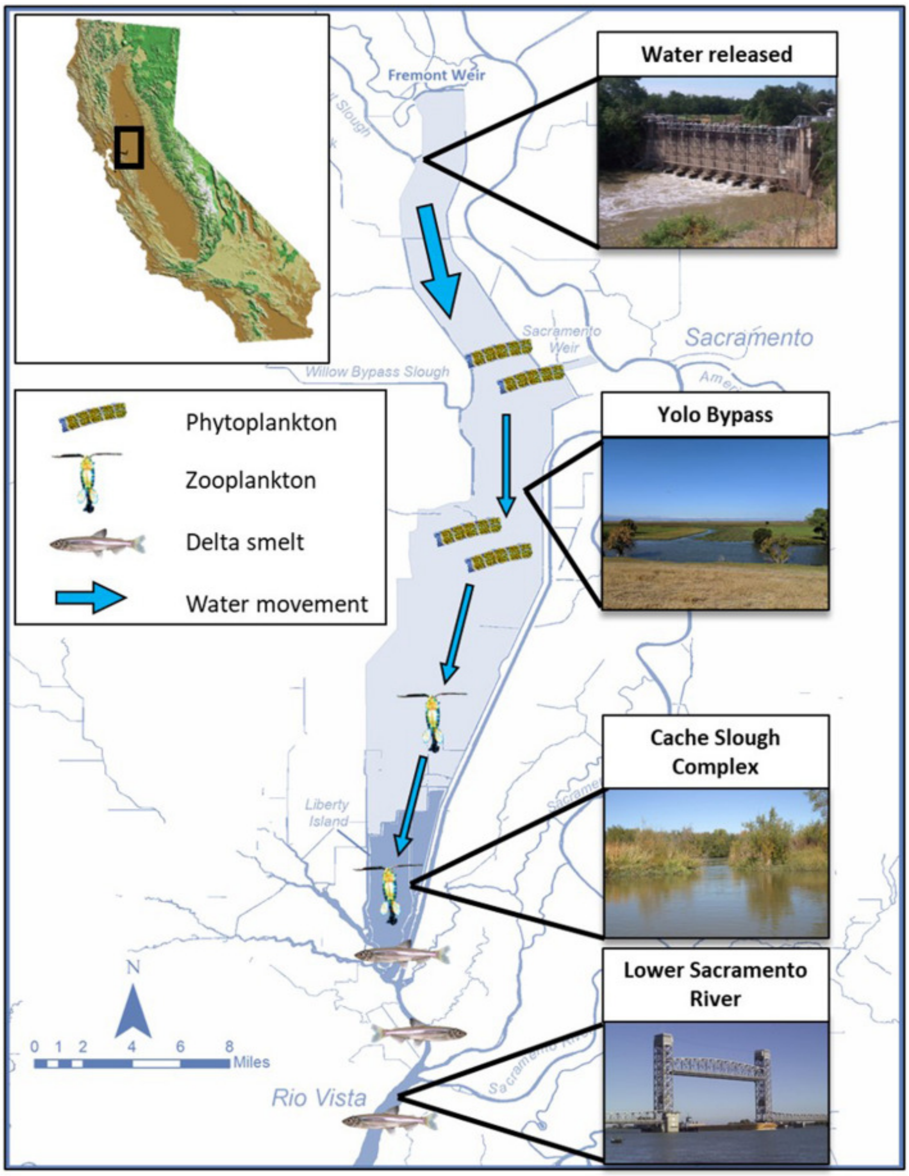

Figure 3

Figure 3

The Yolo Bypass (a tidal floodplain) and Cache Slough Complex (a tidal wetland) are unique places in the San Francisco Estuary because they produce lots phytoplankton and zooplankton. In summer and fall, delta smelt live downstream in the Sacramento River where food has become scarce. Scientists developed a fish food-delivery system that sends river or farm water through the Yolo Bypass to deliver food to delta smelt and other fish downstream, in the Sacramento River [Photo credits: zooplankton photo by Jeff Cordell (USGS), phytoplankton photo by Alexander Klepnev (licensed under Creative Commons Attribution 4.0 International), smelt photo by René Reyes (USBR). Yolo Bypass, Cache Slough Complex, and water channel photos courtesy of California Department of Water Resources. Map of California form US Geological Survey].

the floodplain and delivering it to delta smelt and other fish species may help these fishes survive and thrive into the future. After all the destruction that humans have caused in the San Francisco Estuary and the Sacramento-San Joaquin Delta, we need to make sure that we do everything we can to protect delta smelt and other important species from becoming extinct.

ACKNOWLEDGMENTS

We would like to acknowledge Ted Sommer for his contributions to starting the North Delta Flow Action and food web monitoring in the Yolo Bypass. We also thank our project collaborators, Jim Orlando with US Geological Survey, Frances Wilkerson with San Francisco

State University, and Michael MacWilliams with Anchor QEA. Lastly, managed flow actions would not be possible without scientists and engineers within California Department of Water Resources, as well as local landowners, reclamation districts, and other stakeholders.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

DARIO, AGE: 14

My name is Dario. I live in a small village in Austria. It is full of nature so in my freetime I like to go out with my dogs or climb trees. My parents are both biologist so I got into biology pretty early.

VALERIE, AGE: 13

I am in 8th grade of a middle school in Austria. My hobbies are horseback riding, skating, and dancing. I have got a very old cat and we are getting a dog soon. I also like meeting my friends and listening to some music.

AUTHORS

LAURA TWARDOCHLEB

Laura Twardochleb is a Senior Environmental Scientist Specialist with California Department of Water Resources. She leads monitoring of the effects of the North Delta Flow Action on the Delta food web. Previously, she researched how climate change alters the life cycles of freshwater insects and other organisms in freshwater food webs. She has also studied the impacts of invasive species and urban development on lake food webs. When not working, she enjoys running and hiking with her dog. *laura.twardochleb@water.ca.gov

LEELA DIXIT

Leela Dixit is an early career scientist working with California Department of Water Resources as a Fish and Wildlife Scientific Aid. She works with different scientists on projects focused on the San Francisco Estuary habitat, including salmon and smelt resiliency. She graduated from U.C. Davis in 2018 with a Bachelor of Science degree in Evolution, Ecology, and Biodiversity. She has worked in a variety of fields including microbiology, marine ecology, aquatic toxicology, and outdoor education. Outside of the lab, Leela enjoys playing video games, collecting houseplants, and taking care of her hermit crab.

MALLORY BEDWELL

Mallory Bedwell is interested in using genetic techniques to help with management and conservation of species. In the past, she studied how different species of amphibians evolved. Most recently, she researched how DNA released into the environment, called eDNA, from yellow-legged frogs can be used to detect them in streams and lakes. At California Department of Water Resources, she helps collect samples to examine the overall state of the Yolo Bypass, including water quality, zooplankton, and fish. She plans to use eDNA monitoring techniques to look for rare fish and to better understand zooplankton communities.

BRITTANY DAVIS

Brittany Davis is a scientist and Environmental Program Manager for the California Department of Water Resources. Her work focuses on fish and their habitats in the San Francisco Estuary. She works on projects that help us understand how and why changes to the environment hurt fish. She works with other scientists to devise actions that will improve habitats for fish and help prevent extinction of delta smelt. Previously, she researched how climate change might affect fish in our oceans, near beaches, and in Antarctica. When she is not working, she enjoys outdoor adventures with her family and dog.

JARED FRANTZICH

Jared Frantzich is a Senior Environmental Scientist Supervisor for the California Department of Water Resources. He currently helps to manage over 40 continuous water quality stations throughout the San Francisco Estuary that help provide important data to both water managers and scientists. These stations focus on understanding changes in Estuary water quality that result from habitat restoration actions, water operations, and changing climate conditions. Previously, he spent years researching fish and associated seasonal food-web conditions in the Yolo Bypass floodplain habitat. When he is not at work, he enjoys hunting and spending time on his boat, fishing with his oldest son.

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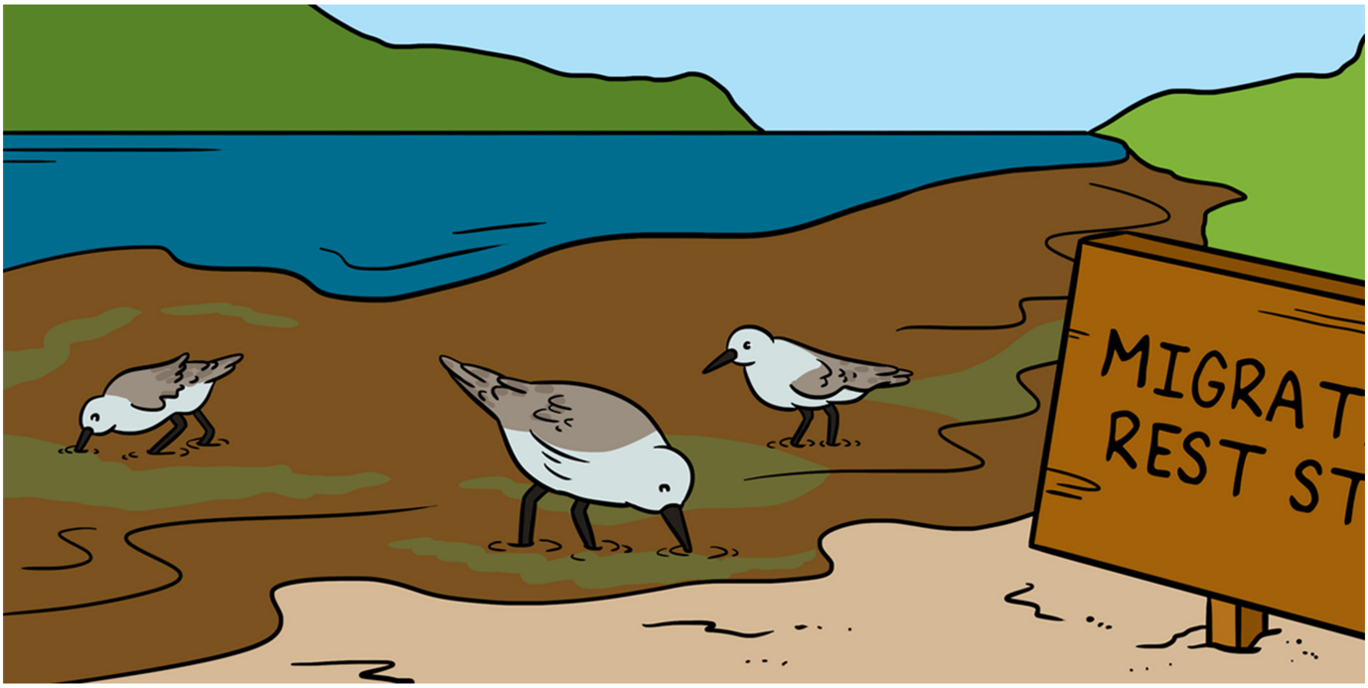

SMALL SHOREBIRDS FEAST ON GREEN SLIME TO FUEL THEIR LONG MIGRATION

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YOUNG REVIEWER:

ROWAN
AGE: 9

Shorebirds wade in shallow waters along shorelines searching for food. More than a million shorebirds visit the San Francisco Estuary each year during their migration to feast on the insects, worms, clams, and crabs that live on or under the surface of the sand or mud. The abundant food in the Estuary provides shorebirds with the energy they need to migrate thousands of kilometers, between their breeding areas in the Arctic and their wintering areas along the Pacific coast of North and South America. Scientists have discovered that, during migration, small species of shorebirds eat a green slime called biofilm that grows on the surface of the mud. Larger shorebirds do not eat biofilm. This article describes how the bills and tongues of small shorebirds help them eat biofilm, what biofilm is, and why biofilm is an important food for those birds during migration.

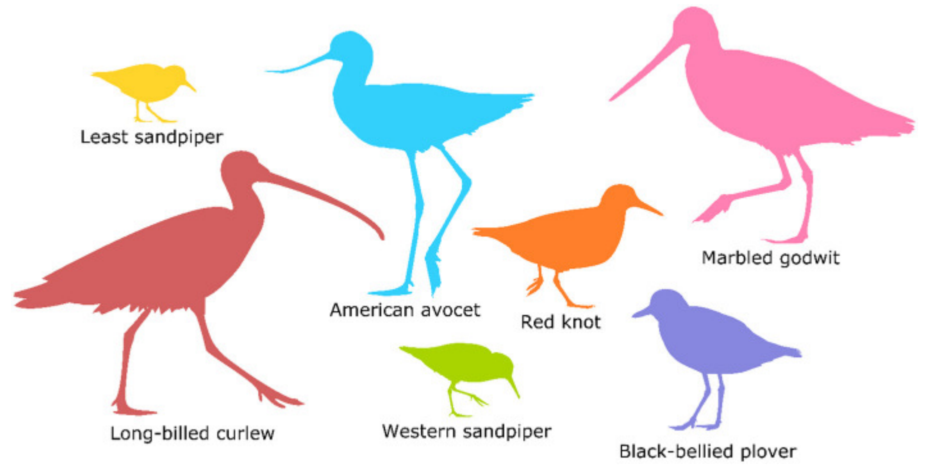

Figure 1

Outlines of seven different shorebird species, showing differences in their sizes and shapes.

SHOREBIRDS COME IN MANY DIFFERENT SHAPES AND SIZES

Shorebirds are often found along shorelines, wading in shallow waters in search of food. They eat **benthic invertebrates**—tiny creatures without backbones, like the insects, worms, clams, and crabs that live on or under the surface of the sand or mud. Shorebirds come in all shapes and sizes, and these differences allow them to eat different types of food so that they can avoid competition with one another (Figure 1). Some, like the marbled godwit, long-billed curlew, and American avocet, have long legs for wading in the water. Others, like the western and least sandpipers, have short legs, so they scurry along the water's edge. The size and shape of a shorebird's bill determine what type of **prey** it can capture and eat. Shorebirds with longer and more curved bills, like the marbled godwit and long-billed curlew, can probe deep into the mud to capture buried prey like worms and clams. The slightly curved shape makes their bills strong and sturdy for probing. Shorebirds with shorter, straighter bills, like the black-bellied plover, red knot, western sandpiper, and least sandpiper, spend more time pecking at prey that live on the surface of the mud because their bills are too short to probe deep into the mud. In addition to benthic invertebrates, scientists have discovered that some species of shorebirds eat a soupy slime called **biofilm** that grows on the surface of the mud [1]. However, not all shorebirds eat biofilm. Only the smallest species of shorebirds eat it, and they eat more of it during their spring migration [1, 2]. But why?

BENTHIC INVERTEBRATES

Tiny creatures without backbones, like insects, worms, clams, and crabs, that live on or under the surface of the sand or mud.

PREY

A creature that is captured and eaten by another creature.

BIOFILM

A slimy mixture of plant-like creatures, bacteria, and detritus that forms on the surface of the mud and provides food for migrating shorebirds and other creatures.

SHOREBIRDS NEED A LOT OF ENERGY TO MIGRATE LONG DISTANCES

Migration is the movement of animals from one place to another during different seasons. Many animals migrate, but shorebirds have some of the longest migration routes of any species. In the fall, as the

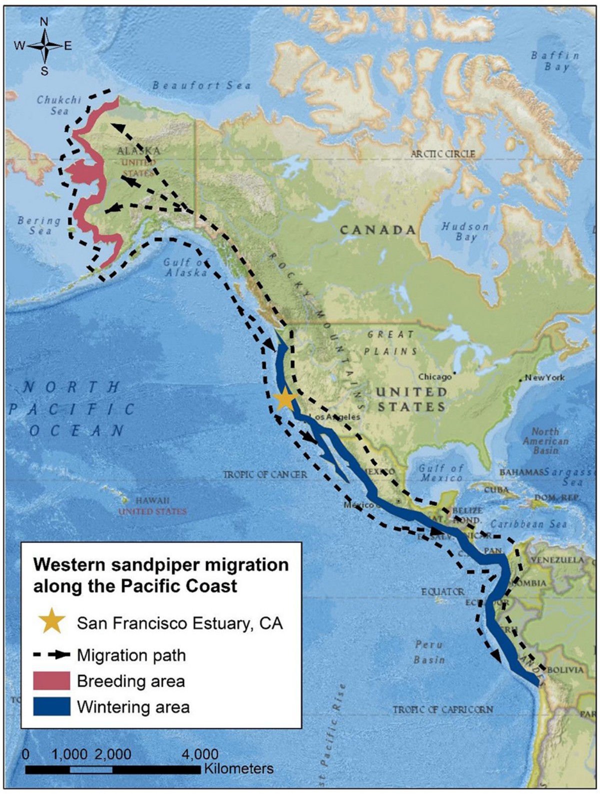

Figure 2

Figure 2

A map of western sandpiper migration between their breeding areas in the Arctic and their wintering areas along the Pacific coast of North and South America. The San Francisco Estuary in California is an important place where more than one million shorebirds stop during their migrations to feast on benthic invertebrates and biofilm (Basemap credits: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp).

weather gets colder, shorebirds on the west coast of North America migrate thousands of kilometers from their breeding areas in the Arctic to warmer areas along the Pacific coast of North and South America, where they spend the winter. In the spring, they migrate back to their breeding areas. Take the western sandpiper, for example. It is a small species of shorebird that weighs 30 g, a little less than a slice of bread. Some western sandpipers migrate from their breeding areas in northern Alaska all the way to wintering areas in Peru. When the winter is over, they migrate back to Alaska (Figure 2). That is a long way for a little bird to travel, and the migratory flights require a lot of energy.

To prepare for migration, shorebirds need to eat a lot of food to save up extra energy. They gorge themselves every day and store the extra food as fat to use as fuel. As they migrate, shorebirds burn energy and use up their stored fat. They stop along their migratory route at places with abundant food so that they can refuel. These refueling stations are called stopover sites. Often, shorebirds spend only a few days at each stopover site, so they need to quickly eat a lot of food before they continue their migration. The San Francisco Estuary on the coast of central California is one of the most important stopover sites in the Northern Hemisphere (Figure 2). More than one million migratory shorebirds visit the Estuary each year to feast on benthic invertebrates and biofilm [3].

WHAT IS BIOFILM?

Biofilm is a slimy mixture of tiny, plant-like creatures, bacteria, and **detritus**. It comes in a range of colors from green to golden brown. Biofilm forms near the shoreline, and it can be seen on the surface of the mud as the tide goes out. During low tide, the plant-like creatures move up through the mud to reach the surface where there is sunlight for **photosynthesis**. They secrete an **ooze** that helps the biofilm stick together, creating a thin layer of slime on the mud. This slime has a lot of nutrients like fats and sugars, and it is an important food for many animals that live along shorelines, like benthic invertebrates, fishes, and shorebirds. These animals compete for biofilm, and, without it, they might not have enough food. The plant-like creatures that make up biofilm need sunlight for photosynthesis, so there is more biofilm on the mud in the spring and summer when there are more hours of sunlight during the day [4]. In fact, the amount of biofilm on the mud increases in the spring when the shorebirds start their spring migration.

DETRITUS

Small particles of decomposing plants and animals.

PHOTOSYNTHESIS

Chemical reactions in plants and plant-like creatures that convert carbon dioxide, water, and light energy from the sun into chemical energy that can be used by creatures.

OOZE

A thick liquid that flows slowly.

HOW DO SHOREBIRDS EAT BIOFILM?

Scientists compared the bills and tongues of small species of shorebirds that eat biofilm to the bills and tongues of larger shorebird species that do not eat biofilm. They found that the tongues of small shorebirds have hundreds of tiny bristles, like a broom, that help the birds scrape biofilm off the surface of the mud (Figure 3A) [1, 5]. Large species of shorebirds do not have bristled tongues (Figure 3B) [1]. Small shorebirds also have shorter, straw-like bills that make it easier to slurp up biofilm, while large shorebirds have longer bills [2, 5]. Even though the longer bill of a large shorebird might look like a straw, it is harder to slurp up biofilm with a longer bill. Longer bills are better for probing the mud.

WHY DO SHOREBIRDS EAT BIOFILM?

Eating biofilm might sound gross, but for a migrating shorebird, biofilm is like an energy drink. Scientists think that small shorebirds might eat biofilm during their migration because it is a quick and easy snack. Why spend lots of time searching for and capturing benthic invertebrates when biofilm is easy to find and easy to eat? Another reason why small shorebirds might eat biofilm is because it is full of nutritious fats and sugars. Biofilm provides shorebirds with nutrients that give the birds fuel to fly long distances [4]. This could explain why shorebirds eat biofilm during migration when they need extra energy for their long flights [2]. It is also possible that small shorebirds eat biofilm during migration to avoid competing for food with larger shorebirds when the birds use the same stopover sites. Millions of shorebirds use

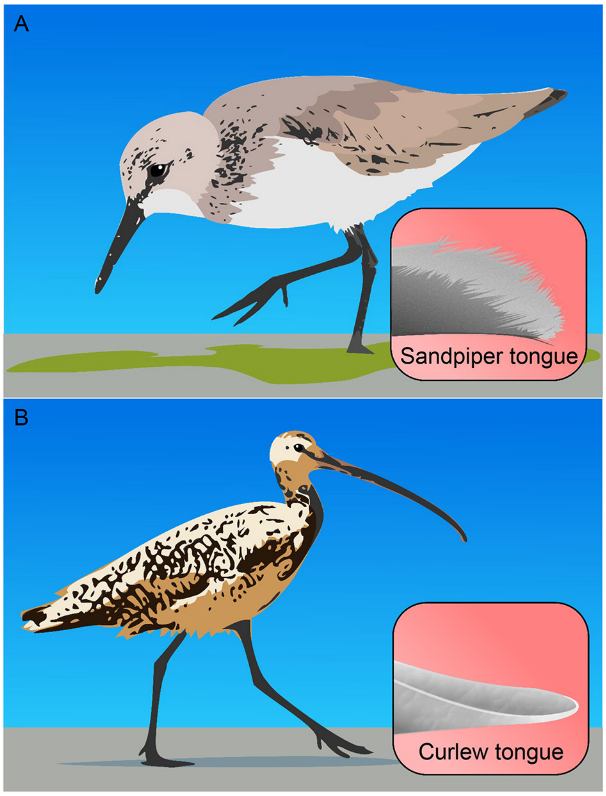

Figure 3

Figure 3

(A) A small shorebird, the western sandpiper, and a magnified image of the tip of a sandpiper's tongue, showing bristles that help the bird scrape biofilm off the mud. The bristles are very thin. Each bristle is the width of three human hairs. **(B)** A large shorebird, the long-billed curlew, and a magnified image of the curlew's tongue, showing smooth edges with no bristles.

stopover sites along the west coast of North America, including the San Francisco Estuary. Imagine if all the birds at a stopover site ate the same type of food. The food would run out very quickly, and many birds would be left without enough energy to continue their migration. By eating biofilm, small shorebirds can avoid competing with larger shorebirds for benthic invertebrates.

Biofilm sounds like a pretty great food. You might be wondering why large shorebirds do not have the tongues and bills to eat biofilm like small shorebirds. It is because large shorebirds need more energy than small shorebirds. Even though biofilm is a nutritious food, it does not have enough energy for a large shorebird. Here is an example: remember the western sandpiper that weighs 30 g and can migrate between Alaska and Peru? Scientists estimate that western sandpipers can consume enough biofilm to make up 60% (more than half) of the energy they need each day during migration [1]. They get the rest of their energy by eating benthic invertebrates. Now, compare that to a larger shorebird, the red knot, that weighs four times as much as a western sandpiper (120 g). If the red knot were to eat the same amount of biofilm as the western sandpiper, the red knot would only get 20% (much less than half) of the energy it needs each day from biofilm [1]. To meet their energy needs each day during migration, large shorebirds eat benthic invertebrates, because they provide more energy than biofilm.

ESTUARIES PROVIDE ABUNDANT FOOD FOR SHOREBIRDS

Biofilm is a nutritious slime that forms a thin layer on the surface of mud along shorelines. Small shorebirds have short, straw-like bills and bristled tongues that help them eat biofilm off the surface of the mud. Large shorebirds are different: they have longer bills for probing and do not have bristled tongues. These differences allow shorebirds to eat different types of food, so that they can avoid competition with one another. Large shorebirds get their energy by eating benthic invertebrates, but small shorebirds feast on biofilm to give them the energy they need to complete their long migrations. Millions of shorebirds visit stopover sites, like the San Francisco Estuary, during migration to gorge on abundant food. Understanding what shorebirds eat helps scientists develop strategies to manage the food available in estuaries and support thriving shorebird populations.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWER

ROWAN, AGE: 9

Hi, I am in third grade. I am interested in medieval castles, battles, and historical weapons. I love archery and I have my own bow that is taller than me. I like to play Legos and listen to stories, and I enjoy skateboarding, roller-blading, and scootering. I enjoy camping with my family and whittling with my pocketknife. I invented a world called "Land of the 19 Dragons." I am making the illustrations and I might write a book about it.

AUTHORS

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Laurie A. Hall is an ecologist at the U.S. Geological Survey, Western Ecological Research Center. Her research is focused on the movement and foraging ecology of waterbirds. She has been studying waterbirds in California for more than 10 years. She received her doctorate in environmental science, policy, and management from the University of California, Berkeley, her master's degree in marine science from Moss Landing Marine Laboratories, and her bachelor's degree in marine science from Southampton College. When she is not staring at birds through her binoculars, she enjoys hiking and camping with her family and friends. Photo taken before 2020. *lahall@usgs.gov

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Susan E. W. De La Cruz is a wildlife biologist and senior researcher at the San Francisco Bay Estuary Field Station of the U.S. Geological Survey, Western Ecological Research Center. She is a San Francisco Bay Area native and has studied wildlife in the region for more than 20 years. Her research is focused on foraging and migration ecology, winter habitat use, survival, and contaminant effects in waterbirds. She received her bachelor's degree in biology and her Ph.D. in ecology from the University of California, Davis. She completed her master's degree in wildlife and fisheries sciences at Texas A&M University. Photo taken before 2020.

ISA WOO

Isa Woo is a biologist at the U.S. Geological Survey, Western Ecological Research Center. She has been studying wetland ecosystems and restoration in the San Francisco Bay and Puget Sound regions for over 15 years. Her research is focused on ecosystem functions, such as invertebrate and biofilm prey resources for fish and waterbirds. Isa received her bachelor's degree in integrative biology from the University of California, Berkeley, and her master's degree in botany from the University of Wisconsin, Madison. She enjoys hiking with her husband and two young kids (ages 8 and 5), and gardening to support insect diversity. Photo taken before 2020.

TOMOHIRO KUWAE

Tomohiro Kuwae is a coastal ecologist and biogeochemist with an interest carbon dynamics and food webs in shallow water ecosystems. He was born in Japan and completed his doctorate there. Tomohiro and his colleagues were the first scientists in the world to discover that western sandpipers eat biofilm as a major part of their diet at a stopover mudflat in British Columbia, Canada. Tomohiro works at the Port and Airport Research Institute in Yokosuka, Japan (https://www.pari.go.jp/unit/ekanky/en/member/kuwae/) where he is currently leading some international blue carbon projects that examine how shallow coastal ecosystems take up atmospheric carbon dioxide. Photo taken before 2020.

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David M. Nelson is a biological science technician at the U.S. Geological Survey's Western Ecological Research Center. He is a Rhode Island native but has worked on waterbird research in the San Francisco Bay Estuary for the past 6 years. He received his bachelor's degree in biological sciences at the University of Rhode Island. When he is not counting birds, he loves to make art and explore. Photo taken before 2020.

JOHN Y. TAKEKAWA

John Y. Takekawa is the operations manager at the Suisun Resource Conservation District in Suisun Marsh near San Francisco Bay. He is a wildlife biologist who has worked on waterbirds and wetlands in the San Francisco Bay, Pacific Flyway, and Pacific Rim over the past 35 years. He has a doctorate in animal ecology from Iowa State University, a master's degree in wildlife biology from the University of Idaho, and a bachelor's degree in forestry from the University of Washington. When he is not chasing birds, he enjoys outdoor activities and watching sports. John is shown holding a Demoseille Crane in Mongolia. Photo taken before 2020.

frontiers FOR YOUNG MINDS

BIODIVERSITY
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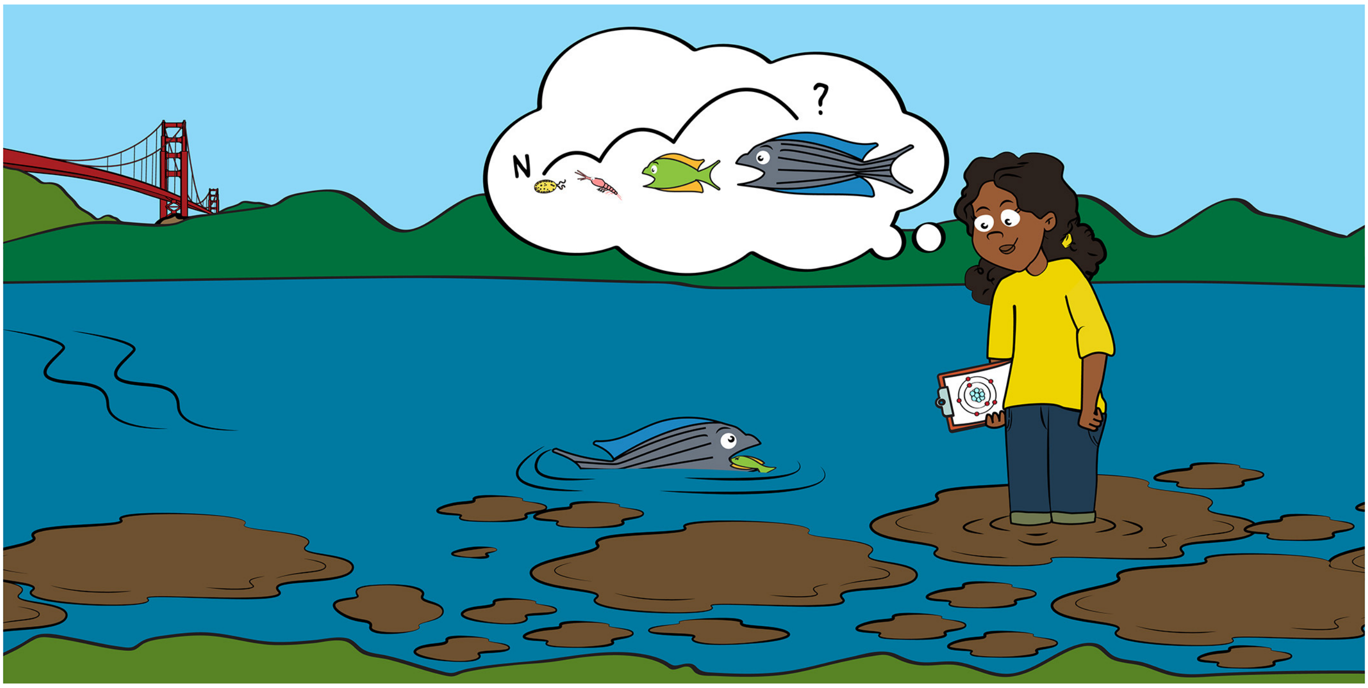

UNTANGLING THE FOOD WEB OF SUISUN MARSH USING ISOTOPES

Caroline L. Newell[1*], *Teejay A. O'Rear*[1] *and John R. Durand*[1,2]

[1] *Center for Watershed Sciences, University of California, Davis, Davis, CA, United States*

[2] *Department of Wildlife, Fish, and Conservation Biology, University of California, Davis, Davis, CA, United States*

YOUNG REVIEWERS:


ANSHUL
AGE: 10


J. W.
AGE: 10


LUVENA
AGE: 12


MATTHEW
AGE: 14


PRANATEE
AGE: 13

What goes on beneath the waters of a marsh? What are the critters below the surface eating? Scientists who study Suisun Marsh in California find out by using a new and powerful tool called isotope analysis. With this technique, scientists untangle the complex food web of Suisun Marsh. This knowledge helps us understand what the connections are between the different types of plants and animals in the Marsh, and how changes to the system may impact these species.

FOOD WEBS ARE DIFFICULT TO STUDY

Nestled in the upper San Francisco Estuary, where rivers meet ocean waters, is California's largest tidal wetland: Suisun Marsh (pronounced "suh-soon") (Figure 1). If you were to dive beneath the water's surface there, you would be amazed by all the activity you find. Over 50 fish species and countless **invertebrates** inhabit the marsh [1].

INVERTEBRATES

Invertebrates are animals without a backbone.

Figure 1

Figure 1

Suisun Marsh is located in the northern region of the San Francisco Estuary in California (United States of America). The call-out box that says "Sampling Location" shows where we sampled in 2011 for the food web isotope study.

The combination of fishes, invertebrates, and their foods makes up what scientists call a food web. Food webs help scientists describe what animals are eating in a place. Food webs organize what animals are eating by splitting them up into **trophic levels**. Trophic levels indicate what a plant or animal eats and what it gets eaten by. The number of trophic levels in a place depends on the number and diversity of species that live there.

In a typical marsh, there are four to five trophic levels. The first level includes organisms that make their own food. These are called primary producers. **Primary producers** in a marsh are typically plants and phytoplankton. They get energy from the sun to produce their own food with the nutrients from the soil, water, and air. The animals that eat the primary producers are the **primary consumers** (usually tiny organisms such as bacteria). **Secondary consumers** (such as mysid shrimp) eat primary producers and primary consumers. The next level up is tertiary consumers. **Tertiary consumers** eat lower-level consumers. A fish that eats mysid shrimp is a tertiary consumer.

How do we figure out what a food web looks like? How do we know what these animals eat and what trophic level they are in? Scientists identify food in animal stomachs to understand food webs. However, because so many animals are small, it is hard to identify the exact foods in their stomachs. This has made it hard for scientists to get a complete picture of a food web. Luckily, a new tool called "isotope analysis" gives scientists a way to map food webs more completely.

TROPHIC LEVEL

Describes the overall categories of a food web. Primary producer, primary consumer, secondary consumer, and tertiary consumer are all different trophic levels.

PRIMARY PRODUCER

Organisms that produce their own food. Plants are primary producers.

PRIMARY CONSUMER

Organisms that only eat primary producers. Zooplankton can be primary consumers.

SECONDARY CONSUMER

Organisms that eat primary consumers and primary producers. Amphipods are an example of a secondary consumer because they eat bacteria and aquatic vegetation.

TERTIARY CONSUMER

Organisms that eat secondary and primary consumers. Striped bass are tertiary consumers that eat amphipods (secondary consumers).

USING ISOTOPES TO STUDY FOOD WEBS

Isotopes are different versions of the same element. To understand what isotopes and elements are, we first need to define what atoms are. Everything around you is made up of tiny building blocks called **atoms**. Atoms are made up of even tinier pieces called protons, neutrons, and electrons (Figure 2A). Different atoms have different numbers of protons, neutrons, and electrons.

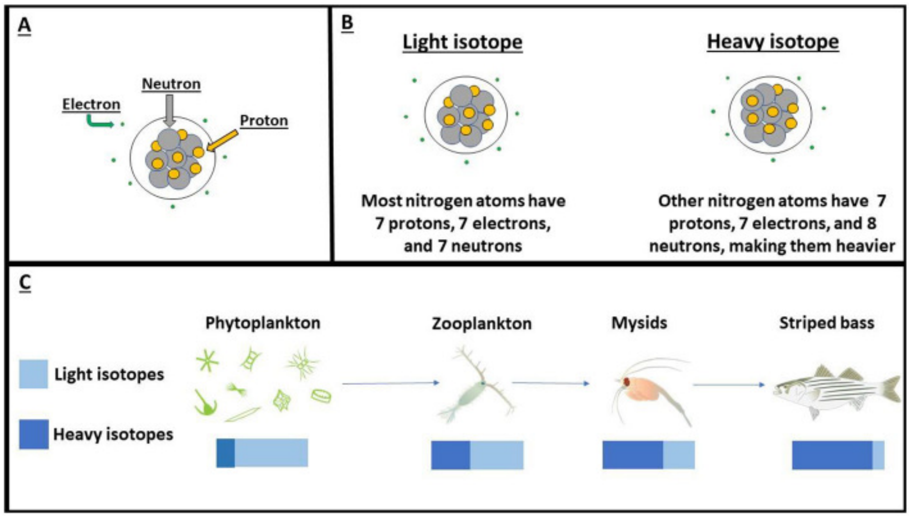

Figure 2

We organize atoms by the number of protons they have and define them as **elements**. For example, nitrogen is an element whose atoms have seven protons. When atoms of the same element have different numbers of neutrons, however, they are called **isotopes** of that element. For example, the element nitrogen has two isotopes. Isotopes with more neutrons are heavier than isotopes with less neutrons (Figure 2B).

To know what trophic level an organism is in, scientists use nitrogen isotope analysis. The difference in isotope weights is the key to nitrogen isotope analysis. Organisms process heavy nitrogen isotopes more slowly than light nitrogen isotopes. This means that when they eat stuff with nitrogen in it, they will keep more of the heavy isotopes which are slow and hang around in the gut. Meanwhile the light nitrogen isotopes rush through and leave the body.

Phytoplankton (primary producers) have less heavy nitrogen isotopes than zooplankton (primary consumers). Mysid shrimp (secondary consumers) have less heavy nitrogen isotopes than a striped bass (tertiary consumer) (Figure 2C). This process is very predictable, so looking at nitrogen isotopes allows scientists to figure out how many trophic levels exist in a food web.

ATOM

A tiny building block of our universe, made up of electrons, protons, and neutrons.

Figure 2

(A) Using nitrogen as an example, you can see that atoms are made up of protons, neutrons, and electrons. The number of protons determines which element the atom belongs to. **(B)** Two isotopes of the element nitrogen. The different number of neutrons gives isotopes different weights, which causes them to behave differently. **(C)** As nitrogen isotopes get passed along the food web, each time an animal eats another they gain more heavy nitrogen. The most amount of light nitrogen is found in the phytoplankton and the most amount of heavy nitrogen is found in the striped bass.

ELEMENT

The type of atom, based upon the number of protons the atom has. For example, the element carbon has 6 protons in each of its atoms.

ISOTOPE

An isotope of an element depends on the number of neutrons it has. Different isotopes of the same element have different behaviors based upon the number of neutrons they have.

To know what animals are eating, scientists use carbon isotope analysis. Carbon is an element whose atoms have six protons. Heavy carbon isotopes have seven neutrons while light carbon isotopes have six. Some primary producers take up more heavy carbon when they photosynthesize sunlight, while others keep more light carbon isotopes.

Once scientists understand which primary producers keep more light carbon and which keep more heavy carbon, they can connect them to animals with similar types of carbon isotopes. So, a plant that has more heavy carbon will pass on more heavy carbon to a primary consumer than a light-carbon plant does for its own primary consumer (Figure 3). By understanding isotopes, scientists can use nitrogen to figure out how many levels there are in a food web and carbon to understand the connections between those levels. Pretty neat stuff!

THE SUISUN MARSH FOOD WEB

In autumn 2011, scientists from the University of California, Davis, wanted to understand the food web of Suisun Marsh in the San Francisco Estuary. To untangle the food web of Suisun Marsh (Figure 1), they collected samples of algae and plants (the suspected primary

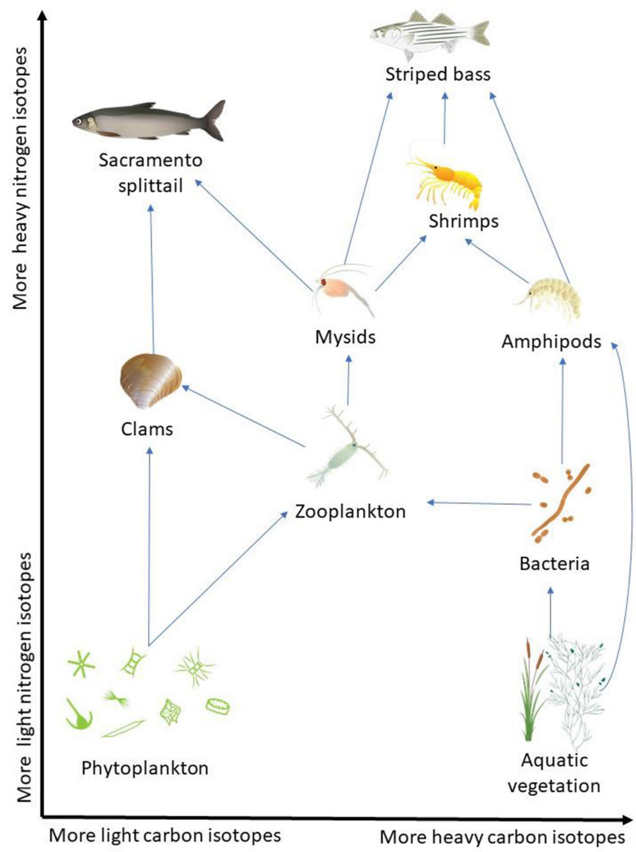

Figure 3

Analysis of isotopes, combined with knowledge from other diet studies, helps scientists understand Suisun Marsh's food web. The primary producers shown here are phytoplankton and aquatic vegetation. The arrows show the path carbon and nitrogen isotopes take as plants and animals get eaten. Diagram does not have every organism in Suisun Marsh but does show how some pieces of the food web fit together [2]. Images in diagram acquired from Integration and Application Network (ian.umces.edu/media-library).

producers). They also collected consumers such as zooplankton, clams, shrimps, and fish—anything they suspected could be in the food web. Then, samples were taken to the lab to look at the nitrogen and carbon isotopes each species had.

The results from the nitrogen isotopes showed scientists that Suisun Marsh's aquatic food web had four trophic levels: primary producers, primary consumers, secondary consumers, and tertiary consumers. Nitrogen isotope analysis confirmed that plants and algae were the primary producers in the marsh. Nitrogen showed only one primary consumer in the marsh – small pileworms. The pileworms had relatively little heavy nitrogen. Secondary consumers had more heavy nitrogen. The secondary consumers were amphipods and mysid shrimp. Striped bass had even more heavy nitrogen, so it was a tertiary consumer (Figure 3).

The results showed large gaps in the food web. Curiously, no primary consumers other than pileworms were found. This likely means we missed other small primary consumers in the marsh (bacteria, for example) because we did not sample them. There were other gaps as well. We know of other fish and invertebrates in the marsh's waters that we did not sample. For example, even though we did not sample Sacramento splittail, we know from other studies that they eat clams. Since it is so hard to study aquatic environments, sometimes it takes putting together information from multiple studies to get a complete answer to our questions (Figure 3).

The data the scientists got from carbon isotopes showed how the different trophic levels were connected. In Suisun Marsh, more heavy carbon belonged to phytobenthos and submersed aquatic vegetation. Phytobenthos are algae that live underwater on the marsh mud. Submersed aquatic vegetation are plants that grow entirely under water (Figure 3). Brazilian waterweed is an example of submerged aquatic vegetation.

More light carbon was found in terrestrial vegetation, emergent aquatic vegetation, and phytoplankton. Plants that grow only on land are called terrestrial vegetation. Bushes, trees, and grass are examples of terrestrial vegetation. Emergent aquatic vegetation are plants that start growing below water and emerge into the air as they grow. Tules are a member of this group. Phytoplankton are microscopic algae that float around in the water and turn nutrients and carbon dioxide into food.

Once the scientists understood the different carbon types of the primary producers, they looked at the consumers in the food web to see which producers they were getting their carbon from. Following the path of light and heavy carbon isotopes, scientists could trace what the consumers were eating. Many invertebrates (such as zooplankton and clams) ate a lot of phytoplankton, decaying emergent vegetation, and decaying terrestrial vegetation. Other invertebrates (such as amphipods) had more of the heavy carbon isotopes, which connected them to submersed aquatic vegetation and phytobenthos.

Higher-level consumers used all of the carbon sources. Most secondary consumers had more light carbon isotopes. This was true for Black Sea jellyfish, yellowfin gobies, and prickly sculpin. Shrimp, on the other hand, had more of the heavy carbon isotopes. Striped bass, one of the most important fishes in the marsh, fell practically in the middle of the carbon spectrum. This means that striped bass ate a large range of other consumers (Figure 3) [2].

FUTURE RESEARCH

Untangling food webs is tricky, but using isotope analysis gets us closer to understanding the mysteries of who eats whom. The knowledge gained from these studies helps scientists predict how climate change and development projects near Suisun Marsh may impact species in the San Francisco Estuary. If these changes wiped out any one species in the food web, everything could change. Predicting how wetland species will react to changes is crucial for management and conservation of these species. Much more work needs to be done to deepen our understanding of how all the plants and animals in this important area are connected so that we can better protect them.

ORIGINAL SOURCE ARTICLE

Schroeter, R. E., O'Rear, T. A., Young, M. J., and Moyle, P. B. 2015. The aquatic trophic ecology of Suisun marsh, San Francisco estuary, California, during autumn in a wet year. *San Franc. Estuary Watershed Sci.* 13:3. doi: 10.15447/sfews.2015v13iss3art6

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2. Schroeter, R. E., O'Rear, T. A., Young, M. J., and Moyle, P. B. 2015. The aquatic trophic ecology of Suisun marsh, San Francisco estuary, California, during autumn in a wet year. *San Franc. Estuary Watershed Sci*. 13:3. doi: 10.15447/sfews.2015v13iss3art6

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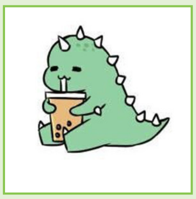
CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

ANSHUL, AGE: 10
Hello! My name is Anshul and I am a fifth grader in North Wales, Pennsylvania, which is close to Philadelphia. I am very interested in Biology and Entomology. I am an active member for the Johns Hopkins CTY program, and my favorite hobby is to read.

J. W., AGE: 10
My name is J. W. and I live on a ranch. I love to pet cows and play with my dogs. I also like whittling wood to make stuff and riding my 4 wheeler.

LUVENA, AGE: 12
Hi, my name is Luvena! I love music, sports, and food. My favorite subjects in school are math and language arts. In my spare time, I enjoy playing piano and reading books with my sister. When I grow up, I would like to be a neurosurgeon.



MATTHEW, AGE: 14
Outside of school, Matthew spends lots of time wrestling, building elaborate Lego structures, and eating chocolate chip cookies. He wishes he had spent less time battling his 3D printer.

PRANATEE, AGE: 13

Hello! I love to bake, especially tarts and pies. In school, my favorite subjects are science, lunch, and recess. I like spending time outdoors and going hiking. I also love going to the beach and have an interest in photography. Watching my favorite TV shows, painting, listening to music, singing, and hanging out with friends are my favorite things to do in my free time. In the future, I would like to either like to be a scientist, or a singer/songwriter and actress.

AUTHORS

CAROLINE L. NEWELL

Caroline L. Newell is a research biologist at the University of California, Davis. She studies fish and food-web dynamics in the Suisun Marsh and upper San Francisco Estuary. She received her bachelor's degree from U.C. Davis with a major in wildlife fish and conservation biology, and minors in statistics and geographic information systems. She loves getting muddy and fishy out in the field and doing science that helps conserve habitat for her beloved aquatic critters. In her spare time, she loves playing soccer. *clsnewell@ucdavis.edu

TEEJAY A. O'REAR

Teejay A. O'Rear is the supervising field biologist for several fisheries projects conducted by U.C. Davis. His primary interest is the relationships among native and non-native aquatic species through time in the San Francisco Estuary watershed. Additionally, his work focuses on rethinking dogmatic ideas such as *native*, *wild*, *non-native*, and *watershed*. In his spare time, he bashes on a guitar and a computer keyboard, and roams all over the wild areas of California.

JOHN R. DURAND

John R. Durand studies the ecology of foodwebs and fish in estuaries. He is particularly interested in how restored and managed wetlands create food and habitat for fishes and other animals, and the effects of climate change on these habitats. Dr. Durand got interested in wetlands and estuaries because he spent a lot of time kayaking in them and had a lot of questions, which eventually led him to get a Ph.D., in ecology at University of California, Davis, where he still works as a research scientist.

BIODIVERSITY
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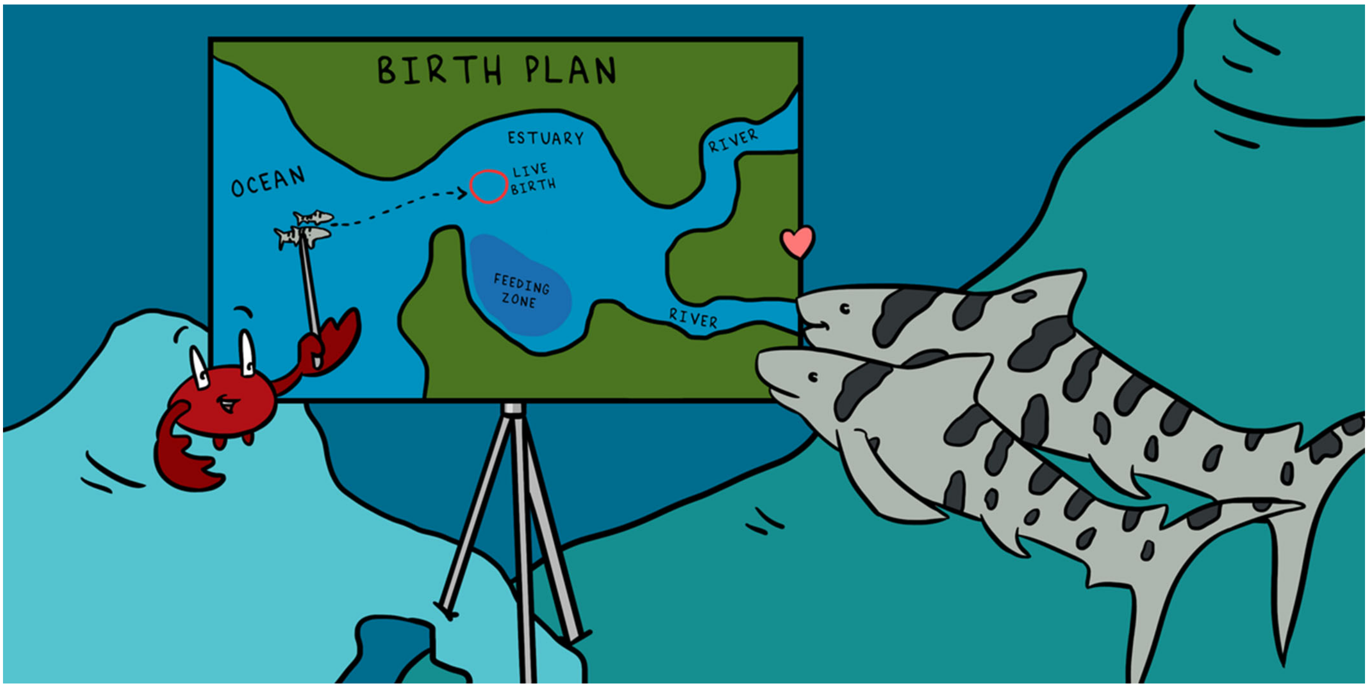

THE CLEVER STRATEGIES THAT FISHES USE TO SURVIVE IN SAN FRANCISCO'S DYNAMIC ESTUARY

Rachel A. Fichman [1*], ***Adi Khen*** [2], ***Malte Willmes*** [3,4], ***Jonathon Kuntz*** [1], ***Alexander R. Scott*** [1], ***James A. Hobbs*** [1] **and** ***Levi S. Lewis*** [1*]

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[2] *Scripps Institution of Oceanography, University of California San Diego, La Jolla, La Jolla, CA, United States*

[3] *Institute of Marine Sciences, University of California, Santa Cruz, Santa Cruz, CA, United States*

[4] *National Marine Fisheries Service, Southwest Fisheries Science Center, Santa Cruz, CA, United States*

YOUNG REVIEWERS:

HANNAH
AGE: 11

VALERIE
AGE: 13

Estuaries are places where fresh water from rivers mixes with salty water from the ocean. Why does this matter? This mixing creates dynamic, ever-changing conditions that fishes must navigate in order to survive. Environmental conditions can change yearly, seasonally, daily, and even hourly. Fishes use many different strategies to adjust to this wild variation. Some are picky and only use certain habitats. Others use many different kinds of habitats and move between them at different times of the year. Adults and juveniles might even live away from each other in different parts of the estuary. In this article, we describe some of the clever strategies that fishes use to survive in estuaries. We also consider how scientists uncover these clever strategies and what each of us can do to help protect the fishes of the San Francisco Estuary and elsewhere.

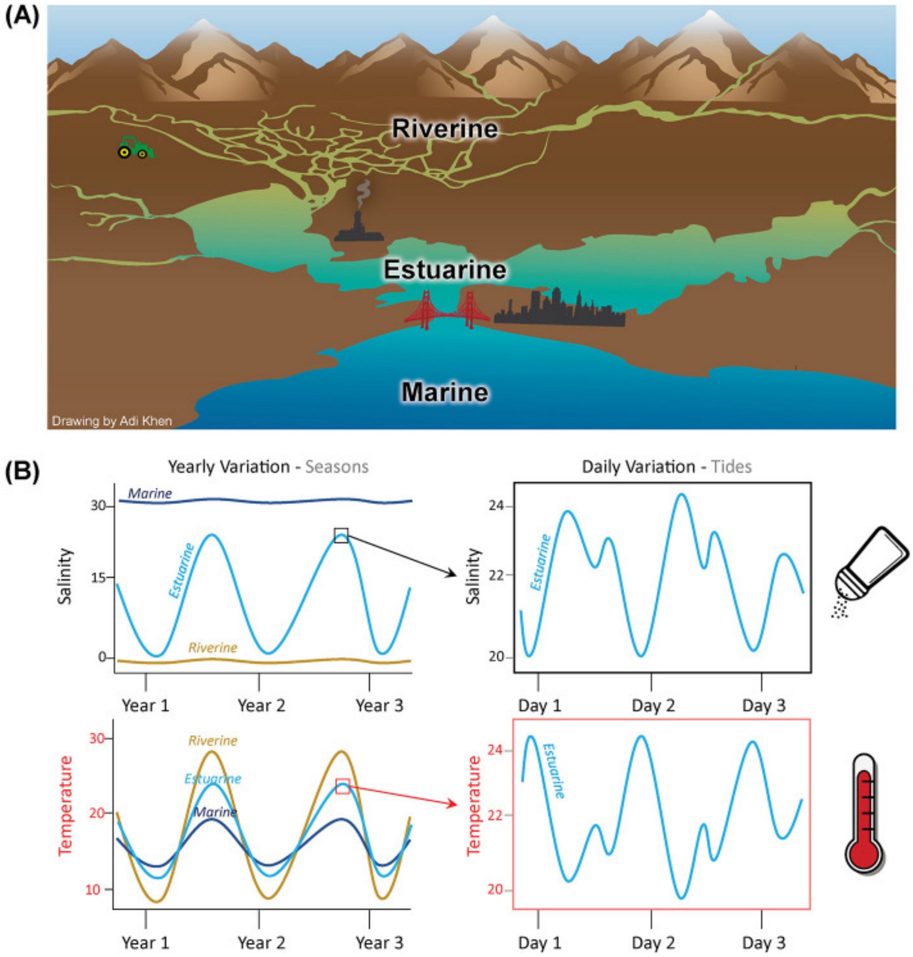

Figure 1

Figure 1

The San Francisco Estuary. **(A)** Fresh water from rain and snowmelt flows as rivers into a network of channels known as the Delta (riverine environment). This fresh water then mixes with the salty water of the ocean (marine environment) and creates the San Francisco Estuary (estuarine environment). **(B)** Salinity and temperature (in °Celsius) change in the San Francisco Estuary with the seasons (left) and daily with the tides (right). Salinity in estuaries is usually between that of marine and riverine habitats, and temperatures are often between those of rivers and the ocean.

WHY IS IT SO HARD TO LIVE IN AN ESTUARY?

An estuary is where fresh water from rivers mixes with salty water from the ocean (Figure 1A). The furthest upstream region of an estuary is influenced most by the **riverine** (river-like) environment, making the water typically fresh or slightly salty. The furthest downstream region is influenced most by the **marine** (ocean-like) environment, so the water is often very salty. Changes in both river and ocean conditions greatly affect habitats inside estuaries, making them dynamic, ever-changing environments (Figure 1B) [1].

RIVERINE

Related to, found in, or produced by rivers or riverbanks.

MARINE

Related to, found in, or produced by seas or oceans.

SALINITY

The amount of salt dissolved in a body of water.

Salinity (saltiness) is one of the changing conditions in estuaries that fishes must deal with. The salinity of estuaries is linked to how much fresh water from rain and snowmelt flows in from rivers. In the San Francisco Estuary, winter and spring are the rainiest seasons. During these wet seasons, more fresh water flows in from rivers, making the estuary less salty. During the hotter, drier months of summer and fall, less freshwater flow results in saltier conditions. The amount of rain and snow can also change from year to year. In a dry year there is less fresh water, making estuaries saltier. Salinity can also change daily and hourly due to the tides. High tides push saltier water further up into the estuary, whereas low tides allow rivers to push fresh water further downstream toward the ocean.

Temperature is another changeable condition within estuaries. The temperatures of estuaries vary with the seasons, getting warmer in the summer and cooler in the winter. Temperatures of inflowing rivers are often the most variable. In contrast, temperatures in the ocean are more stable. Since estuaries lie between riverine and marine habitats, their temperatures are often somewhere between the two. However, some parts of estuaries are shallow and can be rapidly heated by the hot sun during the day, while cooling off at night [1].

These constantly changing conditions make estuaries a tough place for fishes[1] to live. Imagine if it were rainy 1 day, hot and sunny the next, and a blizzard the day after that. You would need to be prepared to adjust your clothing and plans at a moment's notice! Similarly, **estuarine** fishes have figured out many different strategies to help them deal with all this wild environmental variation.

[1] Did you ever wonder when to use the word "fish" vs. "fishes"? "Fish" refers to one or multiple individuals of the same species. "Fishes" refers to multiple individuals of multiple species.

ESTUARINE

Related to, found in, or produced by estuaries.

CLEVER STRATEGIES USED BY ESTUARINE FISHES

The way a fish uses and moves between different habitats throughout its life is called its life history. Different species of fish, and even different individuals within a species, have developed unique life history strategies [2]. These differing life history strategies can be quite clever and are classified into several groups.

Freshwater stragglers, such as Sacramento suckers (Figure 2A), live and reproduce in freshwater riverine habitats. They become strong swimmers to navigate river and tidal flows. They tolerate variable temperatures, but strongly prefer lower salinities. These fishes sometimes travel into the estuary to feed when salinity is low (spring), but otherwise avoid saltier habitats.

Marine stragglers, such as leopard sharks (Figure 2B), live and reproduce in marine habitats, including coastal areas and bays. They tolerate variable temperatures, but strongly prefer waters with higher salinity. Leopard sharks venture into the estuary to feed and to give **live birth** during periods of high salinity (summer) but they avoid certain regions of the estuary during periods of low salinity (winter).

LIVE BIRTH

When offspring are fully developed inside the mother and "born alive." Most fishes lay eggs in nests that are externally fertilized, but some fishes give live birth.

Estuarine residents, such as tule perch (Figure 2C), live and reproduce entirely within the estuary. Like leopard sharks, tule perch also give live birth, but they can tolerate greater variations in salinity. This allows them to remain in the estuary year-round.

Figure 2

Five examples of common life history strategies **(A-E)** that native fishes use in the San Francisco Estuary.

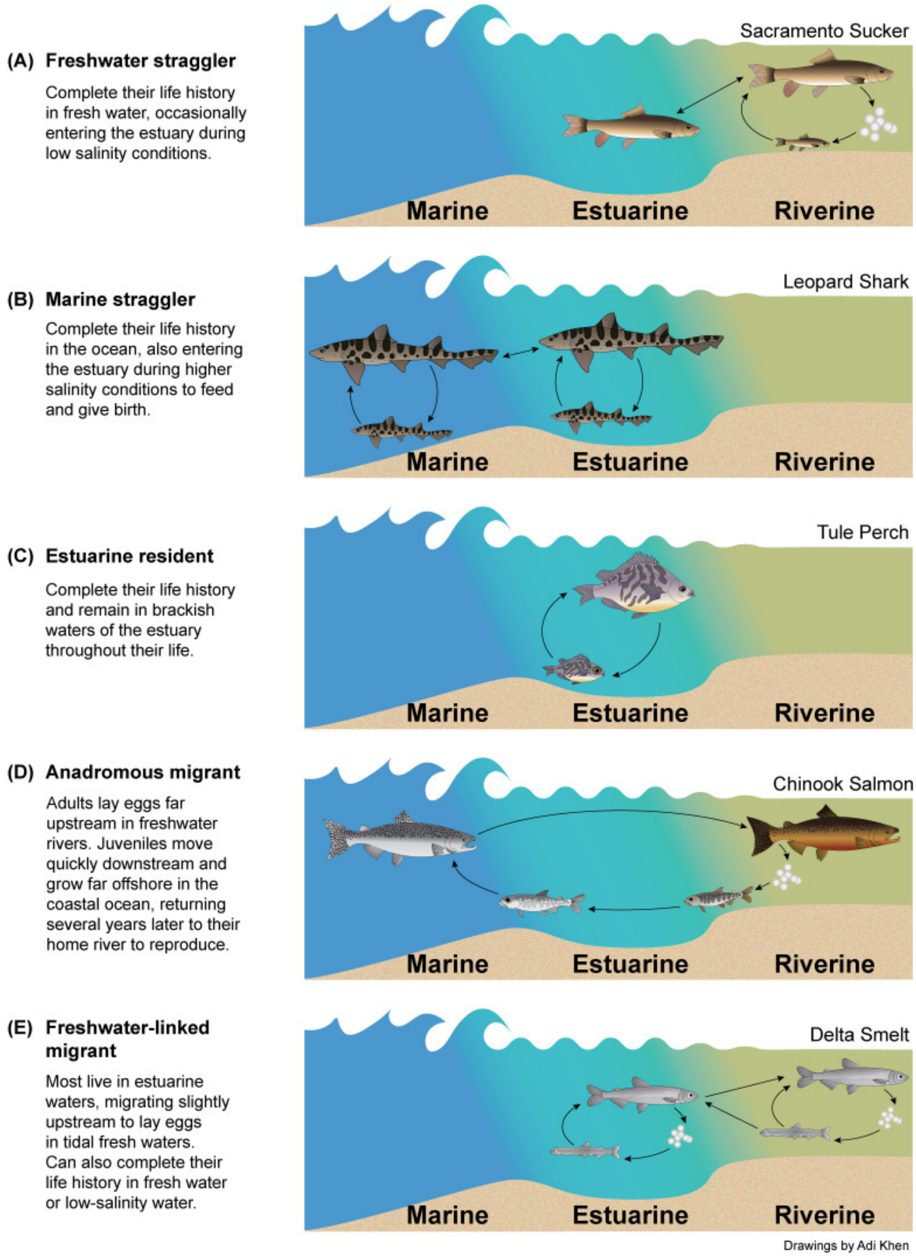

Figure 2

Anadromous migrants, such as Chinook salmon (Figure 2D), live most of their adult lives in the open ocean, migrating quickly through the estuary to lay eggs far upstream in rivers. The fish larvae and juveniles grow up in these rivers and eventually move through the estuary on their way out to the ocean, where they grow into adulthood. For this group, the estuary is like a bridge between juvenile and adult habitats.

BRACKISH

Slightly salty water that is less salty than seawater but saltier than fresh water. Often used to describe water found in estuaries.

Freshwater-linked migrants, such as delta smelt (Figure 2E), can live and reproduce in both freshwater and low-salinity estuarine environments. As juveniles, most live in the somewhat-salty (**brackish**) estuary during summer, migrating upstream into freshwater habitats

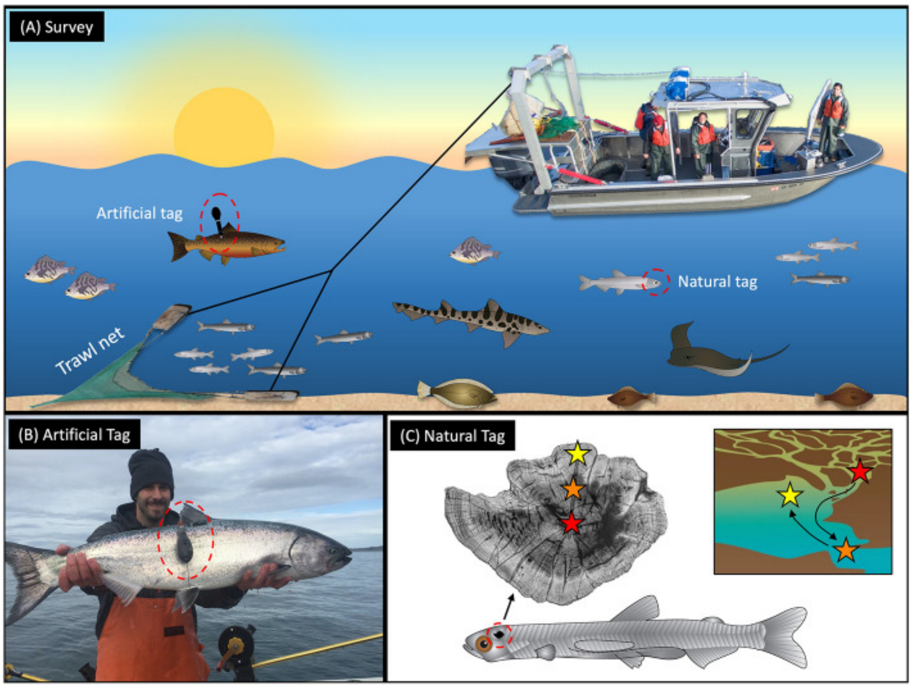

Figure 3

Figure 3

Common methods for studying fish movements. **(A)** Surveys using nets show scientists where fishes live during different times of the year. **(B)** Artificial tags, such as this archival tag on a Chinook salmon, record the movements of individual fish over large distances. **(C)** Otolith chemistry can be used to infer where a fish lived throughout its life. For example, this delta smelt was born in riverine habitats (red star), migrated out into the salty estuary (orange star), then returned to more riverine areas later in life (yellow star). (Photo credit for B: Michael Courtney and Andy Seitz of the University of Alaska Fairbanks).

the following winter, as adults, to lay their eggs. Delta smelt can tolerate some variation in both temperature and salinity, but often move seasonally to find the best habitats with the most food [3].

Although different species tend to use different life history strategies, some fish within a species may not follow those strategies! For example, delta smelt are often considered a migratory species, but we found that not all individuals migrate. While most delta smelt *do* migrate between fresh and estuarine habitats, some spend their entire lives in either riverine or estuarine habitats. This variation is believed to help delta smelt survive unpredictable environmental stress, by making sure that some members of the species are always in different parts of the estuary [3].

HOW DO SCIENTISTS STUDY THE CLEVER LIFE HISTORY STRATEGIES OF FISHES?

Scientists use many methods to discover how fishes survive in estuaries (Figure 3). Each technique provides a different perspective on fish life history strategies.

FIELD SURVEY

When researchers go outside to study plants and animals in their natural habitats, often spread out over different times, days, and locations.

A classic method for studying fishes in the wild is simply fishing for them (Figure 3A). These studies are called **field surveys**. Researchers can use different fishing approaches (hook-and-line or nets) depending on the species and habitats they want to survey. Once fishes are caught, researchers identify, count, and measure them before releasing them unharmed back into the water. By regularly conducting surveys, scientists can create a record of when and where fishes occur, their length and weight, and how fish populations change over time [4].

Another way to study life history is to track individual fish with artificial, human-made tags. Artificial tags allow scientists to discover how individual fish move and use different habitats. However, artificial tags require that tracking equipment be attached to each fish being studied. Some tags consist of small pieces of metal placed under a fish's skin, each with a code inscribed, so when a fish is caught, researchers can identify where it was tagged and how far it moved [4]. For larger fishes, like sharks or salmon, researchers can use archival tags that record a fish's location and environment over time (Figure 3B). Archival tags are attached to a fish's back by performing a minor surgery, similar to a large ear piercing. Once the fish has recovered, it is released back into its habitat to resume a normal life.

Instead of using artificial tags, scientists can also use the chemistry of hard, calcified body parts as natural tags to retrace the movements of fishes. Different natural tags hold different information about a fish's life. Some parts, like scales and fin spines, can be removed and the fish released, with minimal harm to the fish. But, for internal parts like **otoliths**, fishes must be euthanized (killed without pain or suffering) before removal. Otoliths are tiny structures that help with hearing and balance, located in the inner ear of many fishes (Figure 3C). Otoliths grow during the entire life of a fish. As they grow, chemical elements from the surrounding water are deposited into the otoliths. Scientists can then infer where a fish previously lived based on its otolith chemistry, because the chemical elements in the water of rivers, estuaries, and oceans can be very different [5]. Otoliths also grow rings, like inside a tree trunk, that reflect the age and growth of the fish. By combining otolith chemistry with otolith growth, we can even detect the timing of fish movements. This allows scientists to uncover the complex details of a species' life history [3].

OTOLITH

The ear stone of some fishes. Scientists can analyze chemicals in the otolith to reconstruct the movement of a fish and the salinity the fish lived in.

WHAT CAN WE DO TO HELP FISHES IN THE SAN FRANCISCO ESTUARY?

As we have learned, fishes have developed many different strategies to thrive in an estuary. But fishes are not the only users of estuaries. Did you know that, just around the San Francisco Estuary, there are 7.8 million people? That is a lot of humans! Human activities, such as farming, city water use, and pollution, have changed estuaries across the world. This has led to the decline of many fish and wildlife populations whose clever strategies might not fit their environment anymore. Some species, like delta smelt, may even go extinct. Delta smelt are highly impacted by human activities, but we have not yet figured out how to fully protect them. Life history research helps us understand where fishes are born, the habitats they use, and the timing of their migrations. Understanding the life history of fishes is a critical step toward taking action to help protect them long into the future.

This work is not just for scientists! Everyone can help scientists protect fishes in San Francisco and around the world. Here are some ways that *you* can help! You can find out which fishes live near you[2]. You can also learn more about California fishes like those in the San Francisco Estuary from aquariums[3]. With your new knowledge, you can teach your friends and family about the challenges that California fishes face[4]. Do you live near a waterway? If so, you can organize a beach cleanup with friends and family[5]! And always remember to protect all the wild animals and habitats near you by being responsible in the outdoors, picking up litter, and not polluting the environment. Lastly, *you* can become a fish scientist and help us study and protect native fishes!

[2] FishBase https://www.fishbase.se/search.php

[3] Aquarium of the Bay https://www.aquariumofthebay.org/ Aquarium of the Pacific https://www.aquariumofpacific.org/ California Academy of Sciences https://www.calacademy.org/ Monterey Bay Aquarium https://www.montereybayaquarium.org/

[4] California Fisheries Blog https://calsport.org/fisheriesblog/ NOAA for Kids https://oceanservice.noaa.gov/kids/ Otolith, Geochemistry, and Fish Ecology Lab https://www.ogfishlab.com/ Sharks4kids https://www.sharks4kids.com/education The Fisheries Blog https://thefisheriesblog.com/

[5] Ocean Conservancy https://oceanconservancy.org/trash-free-seas/international-coastal-cleanup/start-a-cleanup/

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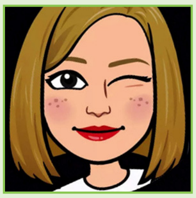
YOUNG REVIEWERS



HANNAH, AGE: 11
I am in 6th grade of a middle school in Austria. I am interested in dogs. My hobbies are gymnastics, other sports, and acting. I have got an old cat and we are getting a dog soon. I also like meeting my friends and listening to some music.

VALERIE, AGE: 13
I am in 8th grade of a middle school in Austria. My hobbies are horseback riding, skating, and dancing. I have got a very old cat and we are getting a dog soon. I also like meeting my friends and listening to some music.

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Jonathon Kuntz is a marine ecologist interested in life history research of sharks. In 2017, he received a B.Sc. in environmental and organismal biology from the University of Utah, where he used stable isotopes to study smooth hammerhead sharks. He has since worked with longfin smelt and leopard sharks, using stable isotopes to better understand their use of the San Francisco Estuary.

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Alec Scott, a Bay Area native, received a B.A. in biology from Carleton College, after which he spent some time doing fieldwork and becoming a divemaster in southeast Asia. He then spent a year working on coral reef ecology at the Scripps Institution of Oceanography. Most recently, he completed an M.S. in marine biology at the University of North Carolina Wilmington, where he studied distributional patterns of Caribbean mesophotic sponges. He is broadly interested in the factors that contribute to the decline of endangered species, and the policy solutions that prevent that decline.

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LEVI S. LEWIS

Dr. Lewis leads the Otolith Geochemistry and Fish Ecology Laboratory at U.C. Davis. He is a general ecologist, studying species movements, growth, and community dynamics of fishes and invertebrates in seagrass beds, coral reefs, and estuaries. His current work focuses on endangered fishes in the San Francisco Estuary, including delta smelt and longfin smelt. In addition to doing science, Dr. Lewis enjoys working with managers to improve conservation and writing "bio-rhymes" about the species and ecosystems he studies. www.accretinglife.com. *lslewis@ucdavis.edu

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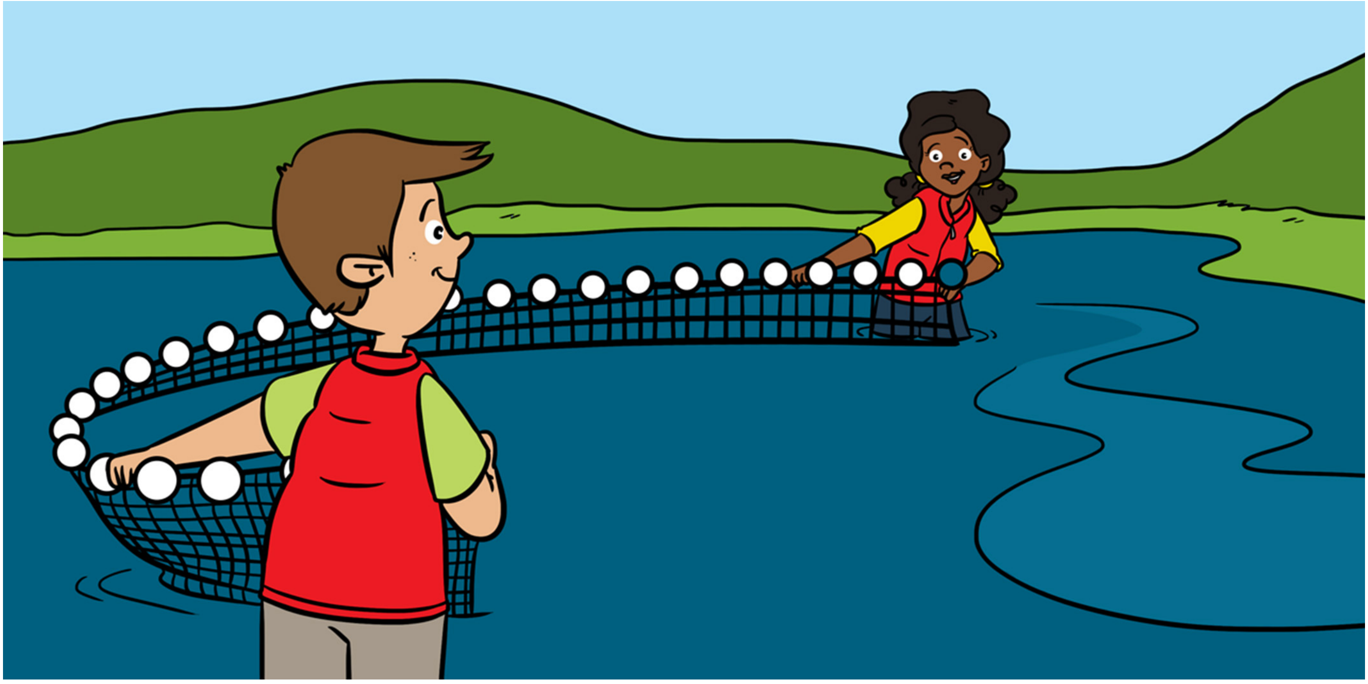

FISH LOVE FLOODS: BENEFITS OF FLOODPLAINS IN SAN FRANCISCO ESTUARY

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YOUNG REVIEWERS:

ISABEL
AGE: 11

MARGARIDA
AGE: 13

Lots of rain can make rivers rise, causing them to spill into low-lying areas called floodplains. Floodplains protect cities from flooding and provide food-rich, safe habitats for freshwater creatures. The largest floodplain of the San Francisco Estuary is the Yolo Bypass. The Yolo Bypass is connected to the Sacramento River and protects Sacramento and surrounding areas from flooding. A twenty-plus year scientific monitoring program in the Yolo Bypass has documented many benefits that this floodplain provides to the Estuary. For example, the Yolo Bypass is a nursery area for baby fish such as young Chinook salmon and Sacramento splittail, and it is an important food bank that transports fish food to the rest of the Estuary. This article discusses some of the benefits that floodplains provide for fish species, and it highlights the importance of long-term monitoring to help scientists and managers make decisions for the benefit of fishes and ecosystems.

WHAT IS A FLOODPLAIN?

When rivers overflow their banks, they produce flooding. The low areas most likely to flood are called **floodplains**. Floodplain habitat is unique because it changes dramatically during flood events, turning from dry land to a large area of water that can resemble a shallow lake. Floodplains can benefit humans by directing flood waters away from cities and towns where lots of people live. However, many floodplain habitats have been built on, removed, or altered by humans, which can result in flooded homes and crops, and may destroy the livelihoods of humans living on the floodplain. Development can also decrease some of the benefits that floodplains provide.

FLOODPLAIN

Low-lying land adjacent to a river that becomes flooded when the river overflows.

However, when floodplains are permitted to flood naturally, they provide great habitats for fish, birds, and other wildlife, by producing food and providing protection. Around the world, many species of fish and wildlife have evolved to consume the large numbers of insects and **plankton** that are produced on floodplains. Floodplains are often important places for endangered animals, and many floodplains are being restored to more natural conditions to try to help these disappearing species. While there are floodplains on rivers all around the world, this article will use the example of a floodplain in California (United States). We will discuss how floodplains are studied and describe some of the interesting results that were obtained.

PLANKTON

Very small plants or animals that drift or float in the water. These can include microscopic plants and invertebrates, as well as egg and larval stages of larger animals.

THE YOLO BYPASS FLOODPLAIN

The Yolo Bypass is a floodplain of the Sacramento River in the Upper San Francisco Estuary. While the main role of the Yolo Bypass is to protect the city of Sacramento and its residents from flood damage, it is also an important area for farming and ranching, and an important wildlife habitat. During the spring and summer, farmers grow beets, tomatoes, corn, rice, and other grains on the floodplain [1]. In the winter, flooded wetlands and farmlands on the floodplain provide a food-rich habitat for migrating birds, such as ducks and geese, as well as other animals.

Flooding on the Yolo Bypass changes from year to year due to the unpredictable rain and snow patterns of the region. During the winter and spring, heavy rain and melting snow from the mountains can cause water levels in the Sacramento River and other nearby creeks to rise, overflowing into the Yolo Bypass. However, flooding is extremely variable, so it does not occur every year [2]. When flooding does occur, the water can come from different sources, which may have unique nutrients and food. Flooding can last anywhere from 1 day to several months. The timing and length of flooding influence the amount of food resources that can build up in the floodplain, as well as whether and how species can enter and use the habitat and benefit from these resources [1].

HOW DO WE STUDY THE FLOODPLAIN?

To understand how the Yolo Bypass changes over time and how these changes affect the animals that use the floodplain, scientists monitor the system year-round. The Yolo Bypass Fish Monitoring Program was created in 1998 and has been providing information about fish, invertebrates, and water quality for over two decades. This is called a long-term monitoring program because it allows scientists to explore trends in the habitat and the organisms that live there, over many years. Floodplains can have highly variable habitats and conditions depending on the season and weather. Thus, the monitoring program is designed to provide information about the floodplain during a variety of different conditions, and it is also designed to adapt to changing conditions. For example, the floodplain provides more benefits to native and endangered fish when it is flooded, so scientists increase sampling during these periods and reduce sampling in the summer, when very few native fish are present in the floodplain.

Scientists in the monitoring program use three different sampling methods to target fish in various habitats and stages of life: the rotary screw trap, fyke trap, and beach seine (Figures 1A–C). To study insects and plankton in the floodplain, scientists use nets of varying sizes (Figure 1D). Once caught, fish, insects, and plankton are counted, identified, and some species are measured and weighed. To study water quality, scientists take daily measurements of the

Figure 1

Figure 1

Sampling methods used by the Yolo Bypass Fish Monitoring Program. **(A)** Fyke traps are used to monitor the movements of adult Chinook salmon, sturgeon, and other fishes moving upstream. **(B)** Beach seines are used year-round to monitor fish living in shallow shoreline habitat. **(C)** A rotary screw trap is used to monitor juvenile fish as they leave the Yolo Bypass. **(D)** Drift nets are used to identify the water- and land-based insects available for juvenile and adult fish as food.

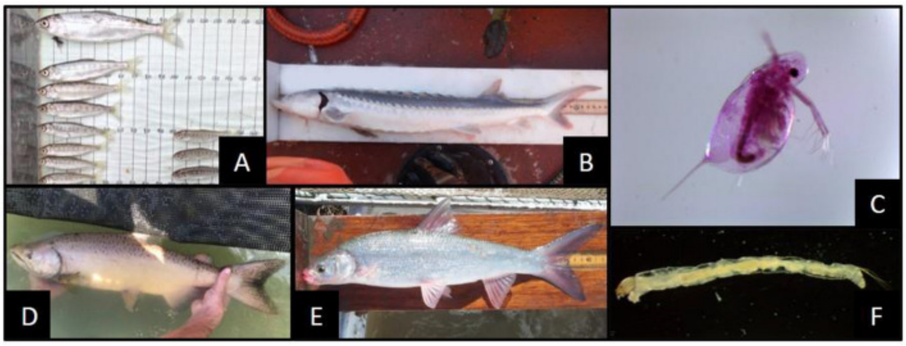

Figure 2

Figure 2

Fish and invertebrates sampled in the Yolo Bypass by the California Department of Water Resources. **(A)** Juvenile Chinook salmon; **(B)** juvenile white sturgeon; **(C)** water flea; **(D)** adult Chinook salmon; **(E)** adult Sacramento splittail; and **(F)** larval midge [Photograph credits: **(C)** Michelle Avila, California Department of Fish and Wildlife; **(F)** Tricia Bippus, California Department of Fish and Wildlife].

water temperature, acidity, oxygen levels, and nutrient levels. Finally, the monitoring program also conducts special studies when there is something especially interesting that needs a closer look, like the question of whether fish grow better in certain areas of the floodplain, or whether there are predators eating threatened or endangered fish species.

WHICH ANIMALS USE THE YOLO BYPASS?

The Sacramento splittail (Figure 2E) is a sleek, silvery native fish species with (you guessed it!) a split, or forked, tail. Splittail respond to the flooding and fast-flowing water that occur in the winter and spring, and they swim into the Yolo Bypass because flooding creates a shallow, protected, warm, and food-rich habitat that is suitable for splittail **spawning** and growth [1]. Once flooding stops, splittail and other fish quickly move out of the floodplain into the Sacramento River, where they continue to grow. For splittail to fully benefit from the floodplain, the land must be flooded long enough to allow adults to swim into the floodplain, spawn their eggs, and for the resulting **larvae** to grow and feed. When fish use a habitat to spawn and grow, this means they use the floodplain as a nursery area. Scientists have found that flooding needs to last at least 1 month for large numbers of splittail larvae to hatch and survive [3]. In years when the Yolo Bypass was not flooded, scientists did not catch many larval splittail, and after a long drought period, scientists thought splittail were going extinct. However, these fish have a talent for bouncing back once favorable conditions, such as flooding and high river flows, return (Figure 3).

SPAWNING

The process of producing and releasing eggs or sperm. For many fish species, spawning only occurs during specific periods of the year or certain environmental conditions.

LARVAE

The early period of an animal's life when it first hatches from an egg and looks and behaves very differently from an adult.

Another fish that uses the floodplain as a nursery is the Chinook salmon (Figures 2A,D). Juvenile (young) salmon arrive in the Yolo Bypass in the winter and spring, when high river flows guide the fish down from their hatching grounds. After spending some time growing in the floodplain, the salmon swim to the ocean to mature, then return to their freshwater spawning grounds after several years. Juvenile salmon that have spent time in the Yolo Bypass have been found to grow

Figure 3

The number of Chinook salmon (pink) and splittail (blue) collected in the Yolo Bypass increases when the Yolo Bypass gets flooded (gray shaded bars, "inundation"). Data were collected from 2015–2019, using a beach seine (top plot) and a screw trap (bottom plot).

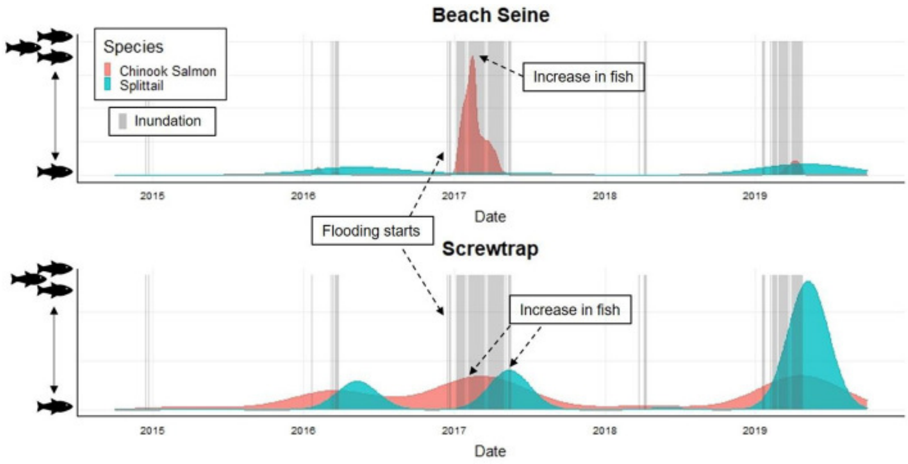

Figure 3

particularly quickly, because the Bypass has much more food than the nearby Sacramento River [1, 4]. Some of the salmon's favorite foods include insects and plankton, including different life stages of midges, flies, and water fleas (Figures 1C,F), which are abundant in the Yolo Bypass [2, 4]. These food resources, which increase during flooding, also feed fish living in other parts of the San Francisco Estuary, once the water in the floodplain drains out into the river. While there are usually more salmon during wet, flooded years when the floodplain is under water for longer periods of time (Figure 3), salmon also use the Yolo Bypass during drier years, but they change what they eat, eating more of the plankton that are available under those conditions [2]. Scientists and **resource managers** are particularly interested in how the floodplain helps Chinook salmon because some types of salmon are threatened or endangered. Understanding how the Yolo Bypass can help juvenile salmon grow faster is useful to organizations that are deciding how to best protect and increase the numbers of these fish.

RESOURCE MANAGERS

People from various government organizations who protect and manage the wellbeing and usage of land, water, and wildlife.

WHY IS MONITORING IMPORTANT?

Hopefully, you now see the many benefits that floodplains can provide for humans and fish. It is important to note that without a monitoring program like the Yolo Bypass Fish Monitoring Program, we would miss a lot of important details about how floodplains function and how they help the broader ecosystem. Long-term data collected by this monitoring program are the reason we know that the Yolo Bypass produces a lot of fish food, and that it is an important nursery area for native fishes such as splittail and Chinook salmon [1, 3, 4]. These results, among others, are helping with the **restoration** of floodplain habitat. With these projects, scientists and resource managers hope to improve the wellbeing of native fishes and the overall health of the San Francisco Estuary.

RESTORATION

Changes to a habitat to improve its quality, usually for the benefit of protected species. Restoration can involve constructing a new habitat or reconnecting existing habitats.

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YOUNG REVIEWERS

ISABEL, AGE: 11

Hello, I am Isabel. I am 11 years old and I really like writing stories. I also like reading. I am really interested in diplomacy.

MARGARIDA, AGE: 13
My name is Margarida, I am 13 years old and I like reading, climbing and writing. I love science, especially anything about black holes and I have absolutely no idea what I want to do when I grow up. I also really like biology.

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Brian is the lead smelt biologist for the California Department of Water Resources. He led the Yolo Bypass Fish Monitoring Program for 8 years and has been studying the endangered fishes of the San Francisco Estuary for over 10 years. He got his bachelor's degree in Wisconsin and his master's degree in California (studying monkeys!).

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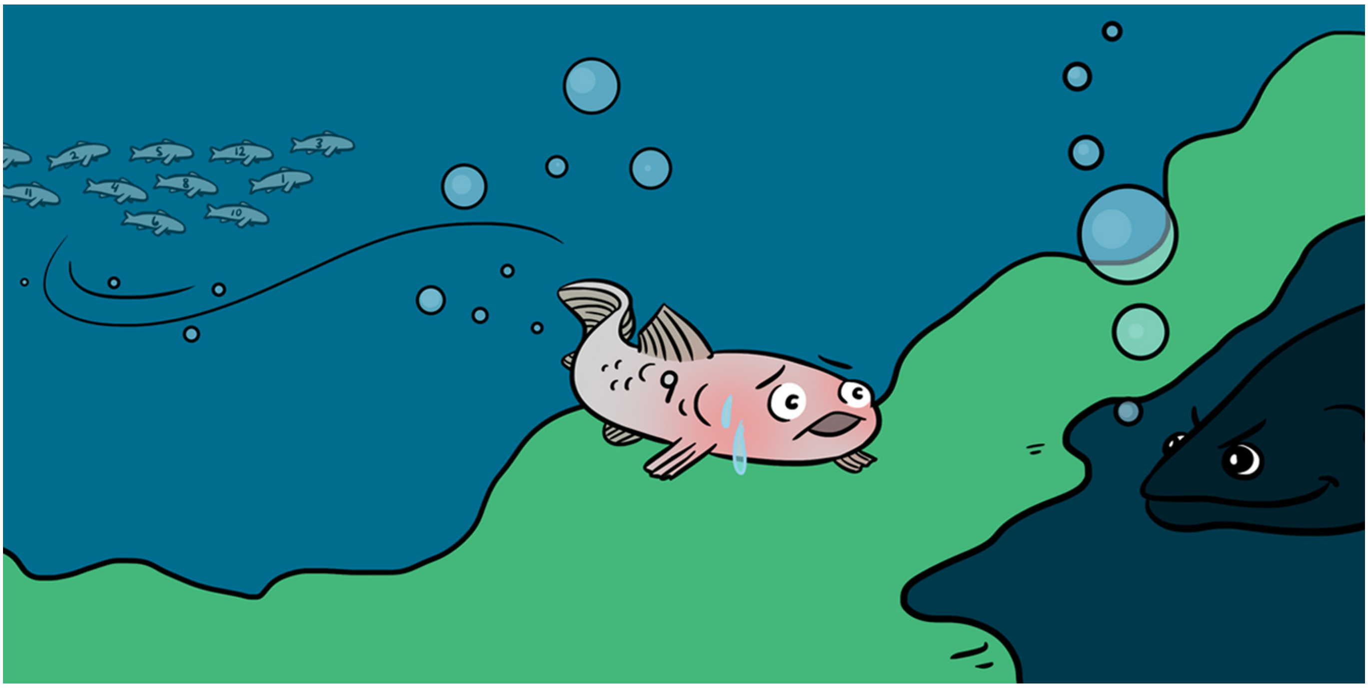

A FISH STORY: HOT WATER AND DANGEROUS BEHAVIOR!

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YOUNG REVIEWERS:

ANUSHA
AGE: 9

SABRINA
AGE: 13

Climate change is warming up water all over the world, including in the San Francisco Estuary. This has caused fish who live there to change their behavior in unexpected ways. All animals, including fish, have regular and specialized behaviors that help them to survive. Fish swim, by themselves or in groups, to move to safer habitats, to find food or mates, or just to avoid danger. Scientists worry that changes to these behaviors brought on by warming water will make estuaries less safe for rare and endangered fish like the delta smelt. In the San Francisco Estuary, we found that warmer waters caused delta smelt to swim faster and further away from their neighbors, and to be eaten more often by predators. All these changes could hurt the ability of delta smelt to survive in the future.

WHAT HAPPENS AS TEMPERATURES GET WARMER?

California has a Mediterranean climate, which means we experience all the seasons including mild, wet winters; spring; dry, hot summers; and fall. When it stops raining and temperatures start to warm up, we can enjoy more outside activities. During warm summers, families might play sports, go to the mountains to camp or hike, or maybe go to the beach, lake, or river for boating or fishing.

Although warm summer temperatures are fun for humans, they may not be safe for fish. Warm temperatures can be quite dangerous to fish if they cannot move to a cooler place or adjust their body temperatures. Humans are okay when it is warm outside because human body temperature is not regulated by the outside temperature. We are **endotherms**, meaning our temperature regulation comes from inside our bodies. Most fish cannot control their body temperatures the way humans can and, as a result, their bodies are the same temperature as their environments. They are called **ectotherms**, meaning their temperature regulation comes from the outside.

ENDOTHERM

An animal that controls its body temperature from the inside, so that body temperature is different from that of the outside environment.

ECTOTHERM

An animal that cannot control its body temperature from the inside, so its body temperature and the outside temperature are the same.

Since ectothermic fish cannot control their body temperatures, warm water temperatures can be very stressful, causing the fish to be sick or act strangely. Hot temperatures do not just affect a single fish; warming can also affect how fish interact with their friends and enemy predators! When an individual fish swims faster or darts around acting scared, it can alter how its friends behave and change how they function as a group [1]. Fish often swim together in large numbers, in groups called schools, and schooling behavior provides fish with protection. When changes to the entire group happen, such as when the fish do not stay close together, it can make them more likely to be injured or eaten by predators.

WHY ARE WE CONCERNED ABOUT WARM TEMPERATURES IN THE SAN FRANCISCO ESTUARY?

The San Francisco Estuary is where freshwater rivers meet the salty ocean. It includes all the rivers and bays in the Sacramento, San Joaquin, Suisun, and San Francisco Bay. Scientists are worried about increasing water temperature in the Estuary because several fish species that live there are important indicators of the healthiness of the Estuary [2]. Several native fish species have already been shown to be sensitive to warm temperatures [3], and some of these species are threatened or endangered, meaning they are at risk of **extinction**.

EXTINCTION

The elimination of an entire species from everywhere on Earth.

One example of an endangered fish in the Estuary is the delta smelt (*Hypomesus transpacificus*). Delta smelt are small fish that used to be very abundant in the Estuary but, because of all the negative changes to their habitat, they are now rare and might go extinct [4, 5]. We suspect that warm temperatures might be one factor contributing to the decline of delta smelt. Climate change is increasing this threat, as it is expected to continue to cause warmer air and water temperatures.

Water temperature is controlled by air temperature in the Estuary. This means that during dry, hot summers, heat waves can really warm up the water and therefore increase the body temperatures of delta smelt. This can make delta smelt unhealthy or impair their abilities to fight for food or escape from predator fish. Delta smelt have been shown to be sensitive to warm water temperatures but, prior to our study, no one had tested how the behavior of these fish changes in response to warm water, or if warm water might lead to a higher chance of being eaten by predators. So, we decided to perform experiments to study these things!

TESTING THE EFFECTS OF WARM WATER ON DELTA SMELT

To understand if a warm water temperature changes the behavior of delta smelt, we conducted experiments in which we placed 12 fish in a large tank, raised the water temperature to a warm 21°C, and video recorded the fish to measure their behaviors for a week. We focused on how warm water changed three types of fish behavior: (i) individual and group schooling behavior, (ii) their reaction to alarming smells that mimicked an injured fish or a predator fish, and lastly (iii) how well the smelt could avoid a predator. For the predation experiment, we added one largemouth bass into each tank of 12 delta smelt. We video recorded this experiment overnight and, in the morning, counted how many delta smelt were injured or eaten by the bass. We performed each type of experiment six times, so that we had enough evidence to tell if the fish were consistently affected by warm temperatures. We also made all our observations at a normal, cool-water temperature of 17°C, to make sure the warm water was the cause of the smelts' behavioral changes.

WARM WATER MAKES DELTA SMELT BEHAVE DIFFERENTLY

We found that warmer water temperatures negatively impacted behavior and survival of delta smelt. We saw that, in warm water, the smelt swam faster (Figure 1A). They also did not swim as close to their neighbors and instead became more spread out (Figure 1B). When we added the smell of an injured fish, delta smelt showed a somewhat normal response of swimming fast and trying to escape, but they never calmed back down after the smell was gone, the way fish in cooler water do (Figure 2). This means that smelt in warm water may continue to swim fast and panic unnecessarily, tiring themselves out. Then, they might not have enough energy left to swim away from an

Figure 1

Warm water changes the behavior of delta smelt in dangerous ways. **(A)** Warm water increases the swimming speed of delta smelt. **(B)** Warm water increases the distance between delta smelt swimming in a group. **(C)** More delta smelt are injured and attacked by a largemouth bass predator when water is warm, probably because the fish are swimming further apart and are less protected by the group. The blue bars represent normal, cool water temperatures (17°C), and the red bars indicate warm water (21°C) (Image credit: T. Treleaven and B. Davis).

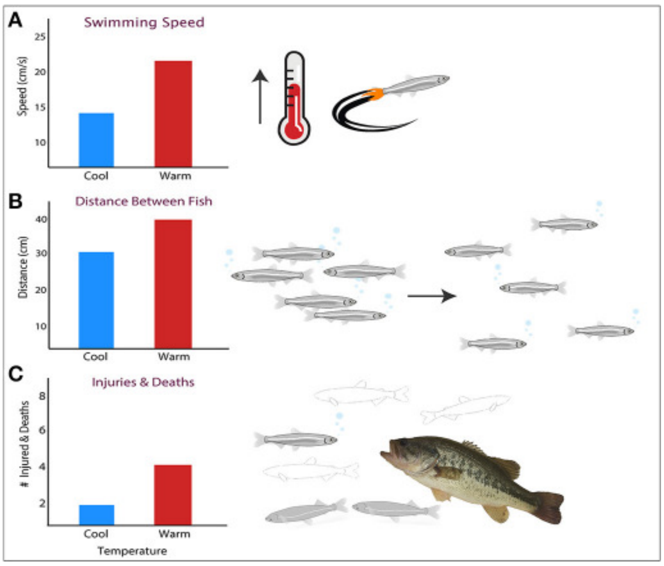

Figure 1

actual predator. Because delta smelt did not swim as close together when they were in warm water, it was easier for the predators to attack them, resulting in a doubling of the number of fish injured and eaten by the largemouth bass (Figure 1C). So, all of our results indicate that warm temperatures changed the behavior of delta smelt in harmful ways. These results provide additional evidence that warming water temperatures may be particularly bad for sensitive species like the delta smelt.

CAN WE HELP FISH TO AVOID WARM WATER?

TIDAL WETLANDS

Areas that are covered in shallow water near land that grow plants and plankton (fish food) underwater and the water is replenished daily with the draining and flooding of tides.

Since higher air temperatures cause water temperatures to warm, fighting climate change is the major long-term solution to the problems faced by temperature-sensitive fish. However, there are some things we can do right now to help protect fish from warm temperatures. In upstream rivers where there are dams, the release of cool water from the deep parts of reservoirs helps keep river channels cool in the areas just below the dams. This can help fish that live in rivers, like salmon. Cooling the water is much more challenging in the Estuary where delta smelt live. There are three ideas that may hold some promise. First, some habitats like **tidal wetlands** and deeper pools could provide at least temporary escape from warm water. Tidal wetlands are shallow-water areas near land that have plants that grow underwater. Tides from the cooler ocean cover these areas in water every day, creating a good habitat for food to grow and for fish to find shelter. Building more tidal wetlands through habitat restoration could be an important way to support delta smelt. Habitats closer to the San Francisco Bay may be especially important since air and water temperatures tend to be a bit cooler there. Unfortunately, habitats cannot be built too close to the ocean because delta smelt cannot

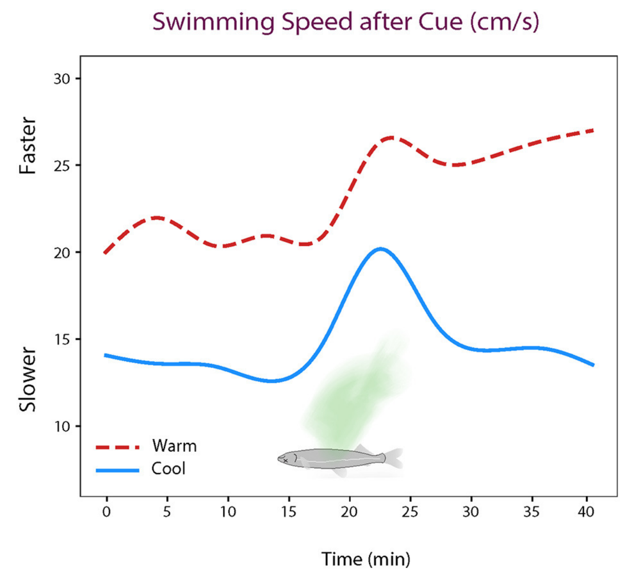

Figure 2

Figure 2

Delta smelt in both cool (17°C) and warm (21°C) water increased their swimming speeds after the smell of an injured fish was added—represented in green. But, in warm water, the fish continued to swim in a fast, panicked way even after the alarm smell was gone. This behavior could tire out the fish and make them more vulnerable to predators (Image credit: T. Treleaven and B. Davis).

PLANKTON

A variety of microscopic animals that drift in the water and provide food for other larger animals such as fish.

tolerate the saltiness of seawater. Second, fish tend to tolerate warm water better when they have more food. Delta smelt eat **plankton**. Because plankton is often scarce in the Estuary, actions that increase the amount of this important fish food could help smelt survive in warm water, at least for short periods. Building more tidal wetlands will help to increase plankton, because tidal wetlands tend to produce lots of food. Last, scientists are currently testing delta smelt that are being grown in a fish hatchery, to see if the smelts' tolerance to warmer temperatures can be increased. If so, these hatchery smelt could potentially be released into the wild someday, to help this endangered species from becoming extinct.

In summary, we found that warming water temperature, as in the San Francisco Estuary, caused delta smelt to change their swimming behavior. They swam faster, further away from their neighbors, and were eaten by predators more often than if they were in cooler water. With continued droughts in California and climate change warming up water all over the world, other species of fish are likely to also change their behavior that might be very dangerous for their survival. If fish cannot adjust to warmer temperatures, avoid predators, find enough food, or we cannot help them by providing cooler areas around the world for them to live, then it is likely more species of fish will become threatened, endangered or eventually go extinct.

ORIGINAL SOURCE ARTICLE

Davis, B. E., Hansen, M. J., Cocherell, D. E., Nguyen, T. X., Sommer, T., Baxter, R. D., et al. 2019. Consequences of temperature and temperature variability on swimming activity, group structure, and predation of endangered delta smelt. *Freshw. Biol.* 64:2156–75. doi: 10.1111/fwb.13403

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YOUNG REVIEWERS

ANUSHA, AGE: 9

I am a 9-year-old girl and I am in 3rd grade. I love to read books, especially fantasy and science-fiction. I have finished reading the Harry Potter, Percy Jackson, Magic Tree House, The Time Machine, and The Lord of The Rings series. I want to be part of this review process because I want to continue to learn and help other kids to learn by volunteering as reviewer.

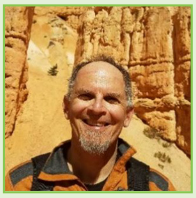
SABRINA, AGE: 13

Sabrina like swimming, backpacking, and being in hammocks. She prefers science fiction to nonfiction because it is a glimpse into what the future may be like rather than retelling what may have occurred. She has a very old and very young dog and is interested in animal behavior.

AUTHORS

BRITTANY E. DAVIS

I am a scientist and environmental program manager for the California Department of Water Resources. My work focuses on fish and their habitats in the San Francisco Estuary. I work on projects that help us to understand how and why changes to the environment might hurt fish. I get to work with other scientists to come up with actions that will improve conditions for fish and to figure out what we can do for delta smelt, so they do not go extinct. Before the Estuary, I researched how climate change might affect fish in our oceans, near beaches, and in Antarctica. When I am not working, I like to go on outdoor adventures with my family and dog. *brittany.e.davis@water.ca.gov



TED SOMMER

Dr. Sommer is lead scientist for the California Department of Water Resources. He has worked on the San Francisco Estuary for 30 years, where his research focuses on endangered fishes and their habitats.

NANN A. FANGUE
I am a professor of physiological ecology at the University of California Davis. In my laboratory, my students and I study fishes—especially those species that are native to California and are threatened or endangered. Our goal is to understand key biological, ecological, and physiological processes used by fishes to respond to environmental changes, to best conserve their natural habitats and ensure their survival. *nafangue@ucdavis.edu

ANNE E. TODGHAM
I am a professor at the University of California Davis. As an ecological physiologist, I am interested in understanding which changes in environmental conditions fish and invertebrates like mussels, oysters, and snails find stressful, and figuring out why. Our work looks at animal physiology, behavior, and what is happening in their cells. I am particularly interested in working with young animals, as we do not think they have the same ability to cope with stress as adults do. I am lucky to conduct a lot of my research with the U.S. Antarctic Program at McMurdo Station. Antarctic fishes are particularly vulnerable to environmental changes, like ocean warming and ocean acidification, since they have lived for millions of years under extremely stable and cold ocean conditions. *todgham@ucdavis.edu

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MURKY MYSTERIES OF YOUNG LAMPREY IN THE SAN FRANCISCO ESTUARY

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YOUNG REVIEWERS:

SAMEEN
AGE: 15

ZAINAB
AGE: 12

Early one morning, a scientist collecting fish in the San Francisco Estuary was surprised to find a young lamprey. She knew lamprey were ancient fish without jaws, bones, or scales, and she wondered to herself: Where else are young lamprey in the estuary? She discovered that although lamprey existed long before dinosaurs, little is known about their lives in estuaries. She and her team decided to gather data from scientists who accidentally caught lamprey while studying other animals. This process of reusing data from unrelated studies, called data synthesis, is an important tool for answering unsolved mysteries. The team uncovered differences in where young lamprey live and that three species live in the San Francisco Estuary, including two species that live half of their lives in the ocean and the other half in freshwater. Knowing where young lamprey live can help scientists protect the habitats lamprey need to develop.

Figure 1

Figure 1

Our discovery of a larval lamprey in the freshwater part of the San Francisco Estuary, or Delta (Illustration by N. Aha Kwan).

LAMPREY IN THE SAN FRANCISCO ESTUARY

With the light from headlamps guiding my way, I set out on a boat with a group of scientists to study predatory fish in the freshwater part of the San Francisco Estuary, also called the Delta. Gathering data for the study required us to stretch a net across the channel to capture large fish (Figure 1). As I pulled up the anchor used to secure the net to the muddy channel bottom, I noticed something wriggling in the mud left on my hand. I called to the other scientists on the boat, and together we identified the wriggling creature as a larval, or immature, **lamprey**. After carefully returning the young fish to the water, I wondered to myself, "What is a larval lamprey doing in the Estuary?"

Before finding the larval lamprey in the Estuary mud that morning, I did not know that lamprey could live in the Estuary when they were that young. Everything I read about these ancient fish indicated that they are **anadromous** and are only found in the Estuary when traveling between rivers and the ocean. Anadromous species use river networks to complete their lifecycles, which requires traveling great distances. When rain falls, it collects in creeks and rivers, which connect to each other and drain into the estuary and then the ocean. Anadromous lamprey also travel from the creeks and rivers where they are born, downstream to estuaries, and ultimately to the ocean. While in freshwater, larval lamprey burrow their eyeless bodies tail-first into mud or sand and **filter feed** by sucking in water and filtering out tiny organisms and decaying matter to eat. Larval lamprey are

LAMPREY

An ancient lineage of jawless and scaleless fish in the family Petromyzontidae.

ANADROMOUS

A large-scale migration, where adult fish travel from the ocean upstream to freshwater, to reproduce.

FILTER FEEDER

Feeding by straining suspended food particles from water. Many animals suspension feed, such as clams, krill, whales, sharks, ducks, and flamingos.

thought to remain upstream in freshwater up to 12 years, after which they begin metamorphosis, which is a physical transformation from one distinct life stage to the next. For lamprey, this transformation from the larval to juvenile stage is where their eyes fully emerge, and they develop complex sucking mouthparts. Juvenile lamprey also become free-swimming, which allows them to migrate to the ocean and **parasitize** larger fish by attaching to the sides of their bodies and feeding off their blood. When lamprey have grown large enough, they return to creeks and rivers, where they build gravel nests and spawn, releasing eggs and sperm into the water and gravel to create the next generation of lamprey [1].

PARASITIZE

A type of relationship where one organism, called the parasite, benefits from another organism, called the host, who is harmed. For lamprey, the hosts are other migratory fish, like salmon and sturgeon.

This understanding of the lamprey's anadromous lifecycle conflicted with my experience finding a larval lamprey, rather than migrating juvenile or adult lamprey, in the San Francisco Estuary, so I decided to investigate it further. If the larval lamprey I discovered in the Estuary was there by mistake, then there would be little evidence of other larval lamprey collected in the Estuary. I began speaking with other scientists studying **benthic** habitats in the Estuary where larval lamprey might be found. I discovered that other scientists were also accidentally collecting larval lamprey in the Estuary, but no one thought to look at all the lamprey catch data together.

BENTHIC

Anything associated with or occurring on the bottom of a body of water.

For some fish species, estuaries are nurseries for young fish to grow before traveling to the ocean [2]. Swimming to the ocean can be dangerous for young fish because the larger fish, birds, and mammals they encounter in the ocean may eat them. Taking time to grow larger while in an estuary can be very important for the survival of young fish. After talking with some colleagues, I assembled a team of researchers interested in understanding where larval lamprey were found in the San Francisco Estuary and why they were there. Together, we developed a two-part hypothesis: if young lamprey use the Estuary as a nursery then: (1) they will be found in the Estuary often; and (2) they will be found in places within the Estuary best suited for their development.

SOLVING THE MYSTERY WITH DATA SYNTHESIS

To test our hypothesis, we pulled together existing data on lamprey catch and habitat conditions collected by other scientists in the Estuary. The process of compiling data from multiple scientists is called **data synthesis**. We found that lamprey were caught by all the scientists whose data we collected and across all areas of the Estuary. This meant that the first part of our hypothesis was correct! As we searched through the data, we noticed there were gaps and differences in the way data were collected. The studies shared with us were not designed to collect data specifically on lamprey, and not all the scientists conducting the studies were trained to identify lamprey. Having imperfect data is a common issue with data synthesis;

DATA SYNTHESIS

A process of bringing together and studying data from multiple projects, with an aim to draw new conclusions or identify similarities to solve scientific questions.

however, there are still many benefits to conducting a data synthesis. For example, data synthesis allows scientists to use data that are freely shared and can include data gathered over many years and across a broad geographic area.

Although there were gaps in the data, our data synthesis taught us that there are three different species of lamprey in the Estuary. Two of those species, Pacific lamprey and western river lamprey, are anadromous and parasitize larger host fish while living in estuaries and the ocean. The third species, western brook lamprey, is not anadromous or parasitic [1]. Instead, this species lives only in freshwater. Freshwater lamprey that are not parasitic spend most of their lives as filter feeders. As adults, western brook lamprey do not parasitize other fish; in fact, the adults do not feed at all. Instead, they live off the energy stored up in their bodies during the filter feeding stage of their life. This life strategy allows lamprey to live in small streams, from which swimming to the ocean may not be possible.

Once we discovered that several species of lamprey lived in the Estuary, we examined our second hypothesis: that young lamprey prefer certain areas of the Estuary. Our team used math to determine the **probability** of young lamprey presence in different areas of the Estuary. This revealed that young lamprey were found in some places more than others. In fact, there was a greater chance that young lamprey would be found in the lower Sacramento River and the **confluence** of the Sacramento and San Joaquin rivers (Figure 2). Our team also discovered that the probability of young lamprey living in the San Francisco Bay and lower San Joaquin River was very low, indicating that lamprey may require specific habitat conditions to thrive. The lower San Joaquin River is known to have higher water temperatures and poor water quality [3], which may be harmful to young lamprey

PROBABILITY

How likely an event is to occur. The value of a probability is a number between zero and one, where zero is impossible and one is certain.

CONFLUENCE

An area where two rivers meet and combine into one. In the San Francisco Estuary, the confluence is the area where the Sacramento and San Joaquin rivers meet.

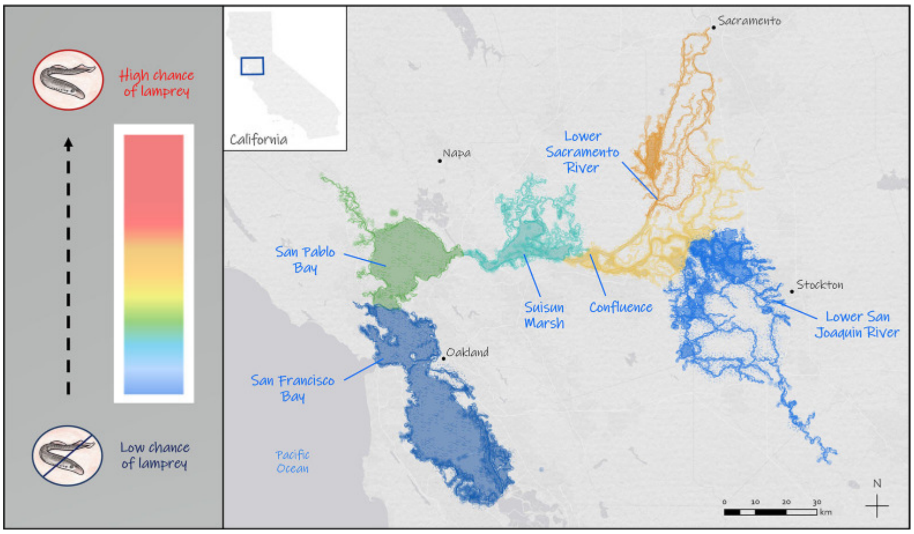

Figure 2

Figure 2

The probability that young lamprey are present in different areas of the San Francisco Estuary. Warmer colors indicate places with the highest chance of lamprey and cooler colors indicate that lamprey are not likely to be found in that area. For example, green in the San Pablo Bay means that there is a 25% chance (1 out of 4) of capturing a young lamprey. Notice that there is no red on this map, which means that no area in the Estuary has a very high chance of finding lamprey.

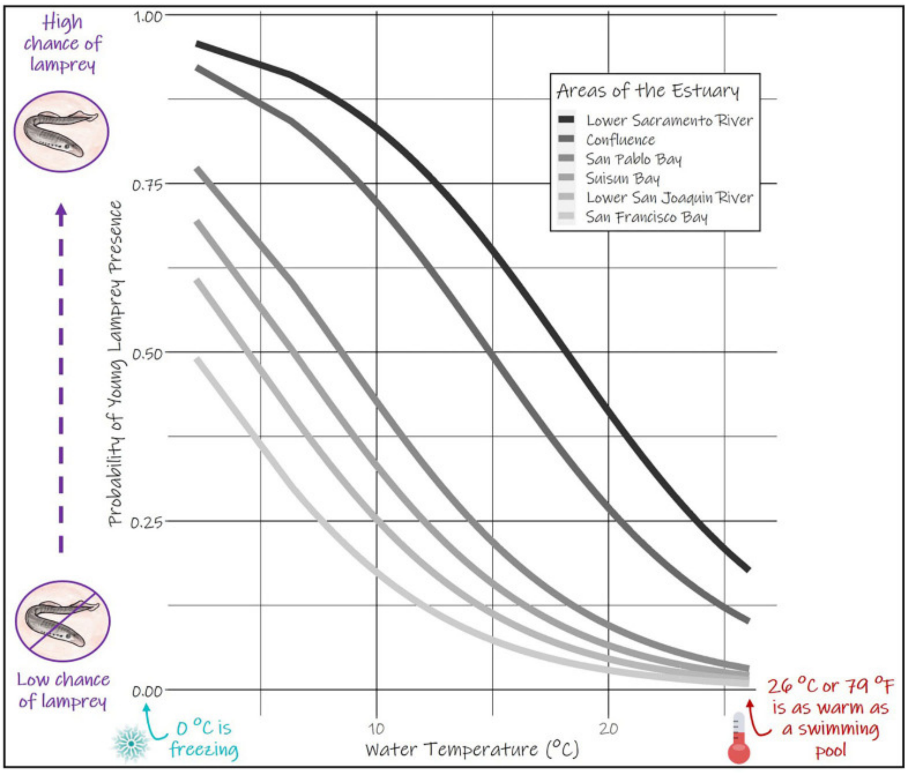

Figure 3

Figure 3

The probability that young lamprey are present at different water temperatures (in degrees Celsius) and areas of the San Francisco Estuary. Notice that in every area of the Estuary, or every line in this figure, there is a higher chance of capturing lamprey at colder water temperatures than at warmer water temperatures. For example, the horizontal line at 0.75 is a probability of 0.75, or a 75% chance (3 out of 4) of capturing a young lamprey in that area and at that temperature. As the temperature increases, the chance of capturing a lamprey decreases.

that filter feed. This is because filter feeding exposes the larval lamprey to chemicals and pollution that may build up in the mud or sand where they feed [4].

The analysis also taught us that young lamprey were more likely to be found where water temperatures were cooler (Figure 3). Like many fish species, the energy required for a lamprey to survive is controlled by temperature. Warmer water temperatures that sometimes occur in the Estuary may stress or harm lamprey [5]. If young lamprey use the Estuary as a nursery, then Figure 3 shows that the cooler temperatures in the lower Sacramento River and the confluence of the Sacramento and San Joaquin rivers may be important places for lamprey to develop.

Like most studies, there are questions left unanswered and new questions asked. Although we discovered where young lamprey are most likely to be within the Estuary, it is still not clear what young lamprey are doing there. The data we compiled were missing details on the developmental stage of each lamprey collected. It may be that larval lamprey feed and grow in the Estuary, whereas metamorphosed juvenile lamprey may only enter the Estuary on their way to the ocean. We cannot know for certain that the young lamprey found in the Estuary were using the Estuary as a nursery or if they were simply traveling to the ocean. However, our data synthesis taught us a valuable lesson—several species of lamprey live in the San

Francisco Estuary and water temperature impacts where we find them. Now, scientists can continue to investigate the remaining unanswered questions by collecting more consistent data to determine which habitats lamprey prefer during each life stage.

HOW WE SHARE WATER RESOURCES WITH FISH

With this new information, we can focus our efforts to protect these areas for future lamprey. California lamprey populations are thought to be declining [1]. Habitat changes and destruction have already restricted known populations to limited areas with less-than-ideal habitat. Understanding how young lamprey respond to warm water temperatures may be critical for protecting these species. As we learn more about lamprey habitat use, more information will be available to help us to improve and expand existing habitat. This is important because lamprey provide many benefits to the environment. For example, larval lamprey feed by filtering tiny organisms and decaying matter out of the water, which helps keep waters clear. Lamprey are also food for other animals, including humans! Protecting lamprey not only keeps them around for us to study, but it also helps preserve the ecosystems that rely on their services.

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YOUNG REVIEWERS

SAMEEN, AGE: 15

Hello, I am Sameen from and I have a strong interest in science subjects, but I like studying biology more. I love to explore natural processes, particularly in aquatic ecosystems. I love to read science articles in the newspaper and learn new languages. Besides, I wish to participate in environmental clubs and field trips. I want to study freshwater ecosystems and molecular biology when I grow up.

ZAINAB, AGE: 12

Hi, My name is Zainab, and I live in a small village. I am excited about species relationships and environmental changes, perhaps why I love knowing about species and ecosystem biology. Apart from that, I want to learn about the history of species and their environment. I like to go to the countryside and see the variety of land plants and animal species. I am also willing for online learning activities related to biology and ecosystems.

AUTHORS

PASCALE AVA LAKE GOERTLER

I am an ecologist who works with fish that travel great distances and are eaten by people. In California, where I live and work, we share the rivers, estuaries, and ocean with the three native groups of fish that I study most often: salmon, sturgeon, and lamprey. My research aims to better understand how to balance the needs of humans and fish for the environment, particularly in estuaries. I am also very interested in data and statistics, and work with other scientists to combine data for a more comprehensive perspective on these fish. *pascale.goertler@deltacouncil.ca.gov

KIMBERLY SHEENA HOLLEY

I am a regulatory biologist with the California Department of Fish and Wildlife. My work is focused on protecting threatened and endangered species that are impacted by long-term changes in their habitats. I work with other fisheries and terrestrial biologists to promote improvements in science and monitoring efforts. New science and collaboration helps me develop management actions that will improve habitat for species in decline. Outside of work, I enjoy exploring the outdoors and all things related to crafting.

NICOLE AHA KWAN

I am a fisheries ecologist with the California Department of Water Resources. I am passionate about advancing fisheries science, to help native species in decline. In my job, I often put on waders and head out into the field to sample fish in river and floodplain habitats. The data from these sampling projects is an important part of monitoring native and endangered species and informing actions to improve their populations. In my free, time I enjoy running with my dog, doing DIY projects, and traveling.

frontiers FOR YOUNG MINDS

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LIVING FOSSILS: STURGEON OF THE SAN FRANCISCO ESTUARY

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YOUNG REVIEWERS

CORTE MADERA SCHOOL

AGES: 10–11

Sturgeon are fish that are considered living fossils. Their ancestors date back over 200 million years, to the same time as dinosaurs. These fish can grow taller than humans (over 2 m), weigh over 160 kg, and live as long as humans. Sturgeon species have special adaptations, such as a vacuum-like mouth and body armor called scutes. There are 27 species of sturgeon worldwide. Two species, green and white sturgeon, are native to California, USA, and are some of the largest animals in San Francisco Bay. Sturgeon populations have declined due to habitat loss, water management, overfishing, poaching, pollution, and climate change. Sturgeon cannot jump over barriers like salmon can, so structures like dams that block water also block sturgeon from reaching their natural spawning habitat farther upstream in the river. Scientists are using new technologies to monitor sturgeon populations and discover the unique behaviors of these dinosaur-era fish in California's rivers and estuaries.

ANCIENT FISH IN A MODERN WORLD

Sturgeon ancestors have been around for more than 200 million years—long before dinosaurs like T-Rex! These fish are large (over 2 m), long-lived (70–100 years), and will **spawn** (reproduce) many times during their lives. However, they are late to mature and only spawn every 2–6 years, which means it takes many years for sturgeon populations to grow. Two species of sturgeon, called green sturgeon and white sturgeon, are found within California waters (Figure 1), especially in the San Francisco Estuary (called the **Estuary** for short) [1]. The Estuary is very important for both of these species throughout their long lives. Sturgeons are among the largest animals living in the Estuary. These gentle and toothless giants spend most of their time slowly feeding on some of the smallest animals. In the past, sturgeon were common in the Estuary, but because of overfishing, habitat loss, and other threats, there are now far fewer sturgeon living in the Estuary. To prevent populations from further decline, these fish have special protections. Green sturgeon in the Estuary are a **threatened species**, meaning they are protected in the United States by a law called the Endangered Species Act. California and other states protect white sturgeon with laws that limit fishing by size, to protect the youngest and oldest fish [2]. In this article, we will look at what makes sturgeon such unique animals and explore ways we can all work to protect them.

SPAWN

To reproduce. Fish release eggs and sperm into the water for fertilization.

ESTUARY

Final section of rivers where the water from rivers mixes with water from the ocean.

THREATENED SPECIES

A species that is likely to become endangered and is protected by the U.S. Endangered Species Act of 1973.

LIVING FOSSILS

Sturgeon are called living fossils because they have changed very little over time. Fish you would recognize as sturgeon first appear in the fossil record during the Triassic period (245–208 million years ago) and their appearance has not changed much since then. However, the fish that sturgeon evolved from are very different from the sturgeon we see today. A major difference is the sturgeon's skeleton. Sturgeon ancestors had skeletons composed of bone, like the human skeleton. But, over time, the material of the sturgeon skeleton changed from bone to cartilage, like your nose and ears. Although most of the sturgeon skeleton is made of cartilage, sturgeon do have some bones in their bodies. Parts of the skull and pectoral fins are bone, and they have bony plates on their skin called scutes. Scutes act as armor. Sturgeon have five rows of scutes that run along their bodies. Details of sturgeon anatomy are shown in Figure 2.

At first glance, many people may mistake a sturgeon for a shark, due to its cigar-shaped body and shark-like tail. However, rather than mouths full of sharp teeth like sharks, sturgeon have toothless, tube-like mouths. Both sturgeon and sharks have ampullae of Lorenzini and all sturgeon and many sharks have **barbels**. Ampullae of Lorenzini are gel-filled pores on the underside of the head that detect electrical signals given off by other living animals in the water and mud. Barbels

BARBELS

A slender, whisker-like sensory organ near the mouth of some fish. Taste buds and touch receptors on the barbels are used to find prey.

Figure 1

Figure 1

(a,b) Green sturgeon are olive to dark green with a yellowish green-white belly. They have green stripes on their sides and belly, a pointed snout with barbels midway between the tip of the snout and mouth, and 8–11 sharp dorsal scutes. They can grow to about 3 m in length. **(c,d)** White sturgeon are gray with a solid white belly. They have a blunted snout with barbels closer to their snout than mouth, and 11–14 dull dorsal scutes. They are the largest fish in North America and can grow to 6 meters.

are whisker-like sensory organs, similar to human taste buds, that are used to taste for prey. Sturgeon and sharks share other similar features, but they are not closely related.

LIFE IN THE ESTUARY

Since sturgeon have poor vision and live in murky waters, they use their barbels and ampullae of Lorenzini to find animals buried within the seafloor. They slurp up their prey by stretching out their **protrusible jaw** a few centimeters to reach the seafloor. When they find food, they suck it up like a vacuum cleaner and crush it in their mouths. The Estuary is home to the many prey that sturgeon eat, such as shrimp,

PROTRUSIBLE JAW

Specialized jaw that allows for the fish to extend or withdraw its mouth.

Figure 2

Sturgeon anatomy. The lower photos show the location of the ampullae of Lorenzini (small pores that detect electrical signals) and the protrusible jaw that allows them to slurp up their prey.

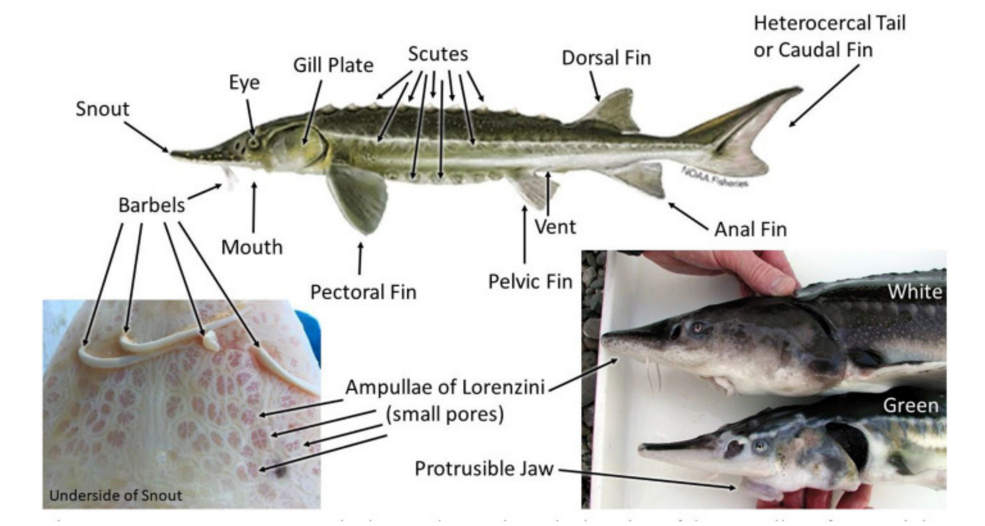

Figure 2

Figure 3

Sturgeon life cycle. Arrows show transitions to new life stages and indicate whether the habitat for each life stage contains freshwater, brackish water, or salt water.

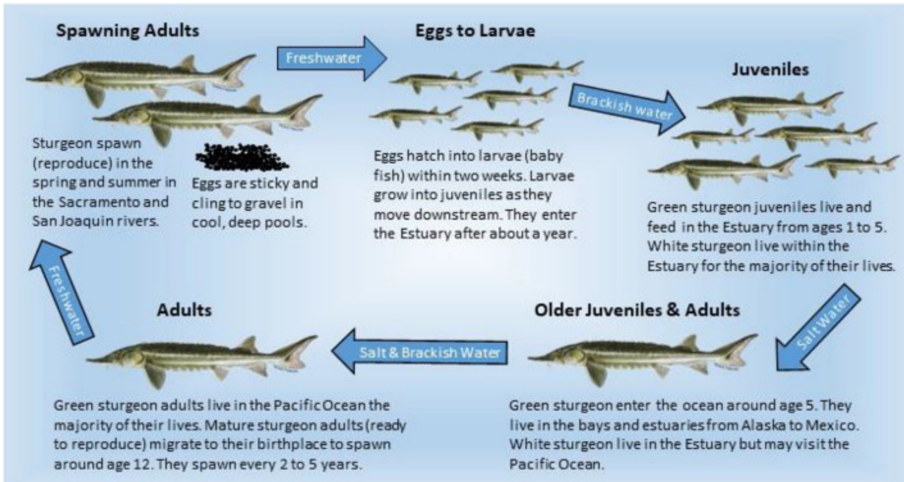

Figure 3

clams, and small fishes. Adults and juveniles of both species feed within the **brackish** (partly salty) water of the Estuary [1].

BRACKISH

Slightly salty water in estuaries that comes from the mixture of river water and ocean water.

All fish need a specific balance of water and salts in their bodies to stay alive. Fish in the ocean are surrounded by too much salt, while fish in freshwater are surrounded by water that has almost no salt. Fish have evolved many ways to move salt and water into or out of their bodies to maintain the right balance, but most specialize in just one habitat throughout their lives [3]. Unlike most fishes, green and white sturgeon can live in freshwater, brackish water, and saltwater (Figure 3). Green sturgeon are **anadromous**, meaning that adults travel to spawn in freshwater, but spend most of their adult lives in oceans and estuaries. White sturgeon are semi-anadromous, meaning that they spawn in freshwater and may spend some time in saltwater, but most of their adult lives are spent in brackish water.

ANADROMOUS

Fish that live most of their lives in the ocean and return to rivers to spawn.

STURGEON LIFE CYCLE

Sturgeon can spawn several times throughout their lives. Green sturgeon live up to 70 years and are able to reproduce around age 15. White sturgeon live up to 100 years and are able to reproduce around age 12. When they are mature, both species return to their birthplaces to spawn, traveling from 100 to more than 1,600 km [1]! Sturgeon have homing abilities that they use to navigate their way home to spawn. The water in each spawning river has a recognizable scent that sturgeon can detect, so they mostly rely on their sense of smell to find the way home [4].

In California's Central Valley, green sturgeon only spawn in the Sacramento River and a few of the smaller rivers that flow into it, while white sturgeon spawn in both the Sacramento and San Joaquin rivers [1]. In the Sacramento River, green sturgeon spawn further north than white sturgeon. Most green sturgeon spawn from April to July, while most white sturgeon spawn from February to May. Sturgeon spawn in deep pockets of the river (4.5 m or deeper) with gravel and large rocks. The fertilized eggs are sticky and glue themselves to the rocks until they hatch into 1-cm larvae. Larvae grow into juveniles, and after about a year spent moving down the river, the juveniles enter the Estuary. Green sturgeon juveniles remain in the Estuary for up to 5 years before they leave for the Pacific Ocean. Green sturgeon adults move in and out of coastal estuaries and bays to feed and grow. White sturgeon usually live in the Estuary for most of their lives. Some may make short journeys into the Pacific Ocean [1].

WHY ARE STURGEON IMPORTANT?

FOOD WEB

All feeding relationships, or food chains, within the ecosystem.

Sturgeon are part of the native ecosystems and **food webs** in California. They are important predators of many small animals. Young, small sturgeon are also food for larger predators. Large adult sturgeon do not have many natural predators, but some are eaten by marine mammals, like California sea lions, and large sharks. Like salmon, sturgeon bring nutrients from saltwater into freshwater environments. Marine nutrients are taken in by sturgeon when they eat prey in the ocean or the brackish Estuary. The nutrients are released into the freshwater environment when sturgeon poop, spawn, or die [5]. Many inland organisms, including trees, smaller plants, insects, and other animals, benefit from ecosystems rich in marine nutrients.

WHAT THREATENS STURGEON POPULATIONS?

Sturgeon population decline is primarily due to overfishing and habitat loss. Because sturgeon take many years to mature, individuals need to survive long enough to reproduce. Sturgeon are prized for their meat and for their eggs, which can be turned into caviar. Sturgeon were overfished (too many fish were removed from the Estuary), and all commercial sturgeon fishing was banned on the west coast of the United States to protect sturgeon populations [2].

Sturgeon have lost access to their habitat because of human activities. Large-scale farming and city development have reduced the amount and quality of sturgeon habitat. These activities not only directly remove habitat but also increase pollution in the environment. Barriers like dams also block sturgeon from reaching the best spawning habitats [2]. Some barriers have been removed, but sturgeon still have limited access to these spawning habitats. Before sturgeon populations can recover, these barriers must be removed or appropriate sturgeon passages must be built.

HOW CAN WE HELP STURGEON?

Scientists in California study sturgeon in nature and in labs to better understand and protect these species. Scientists catch and tag sturgeon to understand their growth, spawning behavior, and habitat use. In lab studies, scientists run experiments on sturgeon of all life stages, to understand their swimming abilities. Scientists work together on projects that will benefit sturgeon and help the species to recover.

There are several easy ways that *you* can help sturgeon, too[1] . First, conserve water while washing dishes, bathing, and brushing your teeth. Also, keep dangerous chemicals out of your home and our waterways by making your own household cleaners or purchasing cleaners that are labeled non-toxic. Look for the Safer Choice label if you are in the United States. Properly dispose of trash, old paints and chemicals, and recyclables in special facilities, so that they do not end up polluting the environment. You can also continue to learn about sturgeon, their habitat, and species conservation[2] . If you live in California and fish for white sturgeon, follow all fishing regulations[3] and report any sturgeon catch. Fishing for green sturgeon is not allowed. If a green sturgeon is caught, it must be released without being removed from the water. Combined, the research performed by scientists and the actions that we all take in our daily lives can help to preserve these living fossils for many more years to come.

[1] http://go.usa.gov/xvSRn

[2] https://www.fisheries.noaa.gov/species/green-sturgeon

[3] wildlife.ca.gov/Regulations

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YOUNG REVIEWERS

CORTE MADERA SCHOOL, AGES: 10–11

We are a fifth grade class, excited about all things science. Since we live in the San Francisco Bay Area, we love to learn about the amazing wildlife and the natural environment around us.

AUTHORS

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interested in ecology, behavior, and trophodynamics (feeding, food webs) of fish. I am especially interested how human alterations of habitat (pollution, engineered rivers, development) affect fish. *page.vick@noaa.gov.

JOHN T. KELLY
Dr. John Kelly, CDFW. I am currently the statewide sturgeon coordinator for the California Department of Fish and Wildlife. I have always been interested in the behavior, physiology, and ecology of fishes. I started my career studying coral reef fish in Florida, and since then I have studied a wide range of species, including great white sharks, salmon, and sturgeon. I am interested in migration and movement, and especially interested in fish that move between fresh and saltwater. I first started studying sturgeon in 2000, when I was working on my Ph.D. at the University of California, Davis. *john.kelly@wildlife.ca.gov.

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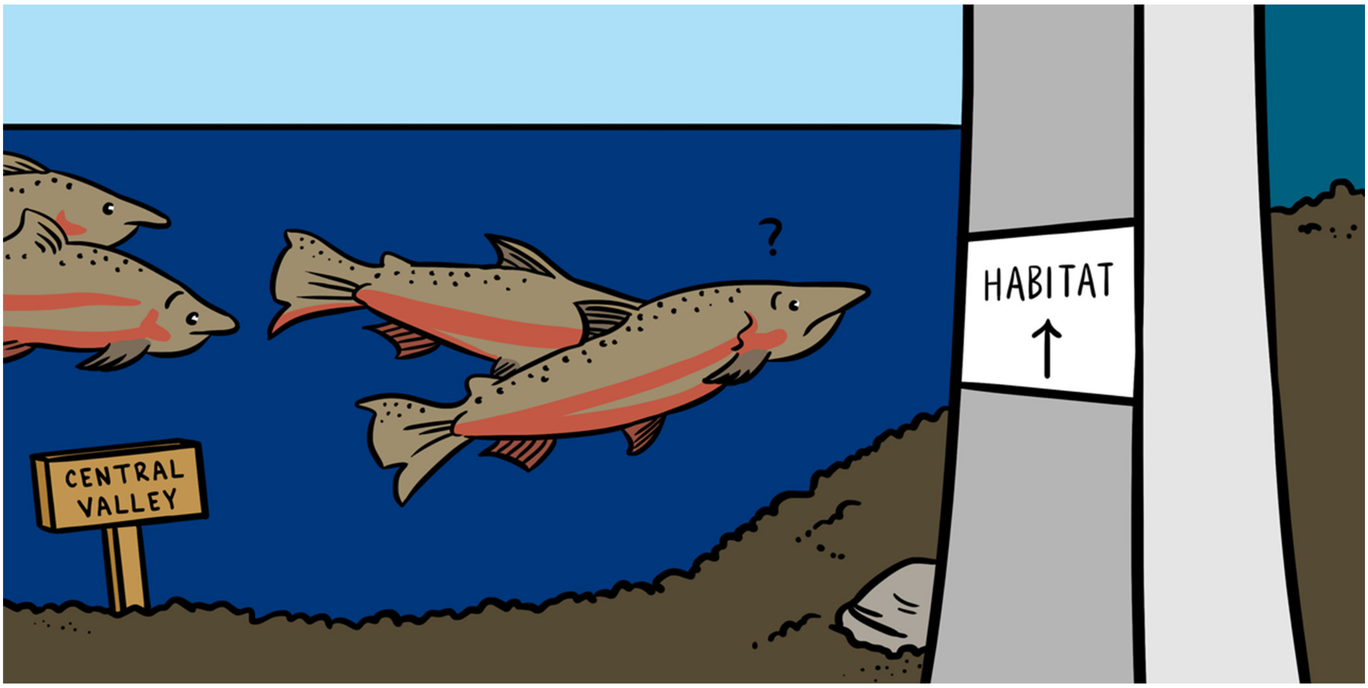

THE CENTRAL VALLEY SALMONID STORY: SIX MILLION YEARS IN THE MAKING

Hilary Glenn**, *Stacie Fejtek** and *Jacob Rennert*

California Central Valley Office, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Sacramento, CA, United States

YOUNG REVIEWER:

SIGNE
AGE: 10

For over six million years, salmon and steelhead (known as salmonids) have returned to the California Central Valley. After swimming under the Golden Gate Bridge and through the San Francisco Bay, adult salmonids swim hundreds of miles up the Sacramento or San Joaquin Rivers. Before dams were built, three out of the five salmonid species swam from the Central Valley into high-elevation, cold-water streams within the Sierra Nevada, southern Cascades, and Coastal Mountain ranges to finish their life cycles. Unfortunately, barriers such as dams cut-off salmonids from their home streams. When salmonid populations decrease, the effects are felt across the ecosystem—everything from microbes to humans feels the disconnection between the rivers and the ocean. Governmental agencies and their partners are teaming up to restore Central Valley salmonid populations by reconnecting them to their habitats and putting them back into high-elevation streams.

SALMONIDS: A CONNECTION BETWEEN THE OCEAN AND THE MOUNTAINS

SALMONIDS

A group of fish that spawn in fresh water and have adipose fins. Some, like steelhead and salmon, live in the ocean as adults and migrate to the river to spawn.

ANADROMOUS FISH

Fish that are born in rivers (freshwater), then spend their adult lives in the ocean (saltwater), and then return to rivers to reproduce.

Salmon and steelhead are two closely related fish that are complicated and fascinating. Together, they form a group called **salmonids**. Salmonids are **anadromous fish**, meaning they are born in rivers and then migrate hundreds of miles from rivers to the ocean and back again, almost to the exact spot they were born, to reproduce and then die. Salmonids are a connection between the ocean and the mountains. In California (United States), anadromous fish evolved to migrate through specific rivers along the Central Valley and during different seasons. The Central Valley is an unusual place to find a fish often found in the ocean because the water is very different from the water in the ocean. The complex life cycle of salmonids helps them survive these differences, but also exposes them to many threats that could lead to their extinction. Their extraordinary journey through diverse habitats makes these fish important to many different ecosystems throughout California. When given enough water and correct temperatures, salmonids have the ability to adapt and thrive in the rivers of the Central Valley [1]. Since the early 1900's California's Central Valley has changed so much that scientists are not sure how much longer salmonids will survive. But, if people act quickly, we can still help these important species survive and thrive once again.

SALMONIDS EVOLVED WITH THE CALIFORNIA LANDSCAPE

RUN

The time of year a salmonid travels from the ocean to the river. The Central Valley has four runs of salmon (winter, spring, fall, and late-fall) and one of steelhead.

The Sacramento and San Joaquin Rivers in the California Central Valley may seem like strange places to find a fish that spends most of its life in the ocean, given the Central Valley's distance from the ocean and high temperatures during the summer months. Yet, salmonids have lived there for millions of years. When a particular group of salmonids migrates together from the ocean to freshwater, it is called a **run**. Each species' run occurs at a different time of the year, the same way some schools have different times for lunches so that the entire school is not using the cafeteria at the same time. Run timing divides Central Valley Chinook salmon into four special groups from which their names are based: fall-run, late fall-run, spring-run, and winter-run (Figure 1). The migration timing of the late-fall Chinook salmon run overlaps with that of Central Valley steelhead.

SPAWNING

When a female fish releases her eggs into her rock nest (called a redd).

Adult fall-run salmon migrate into rivers during the fall when temperatures begin to drop. After migrating, they immediately begin building nests (also called redds) and **spawning** (laying eggs) in rivers at lower elevations on the Valley floor. Adult winter- and spring-run salmon migrate into the rivers in the Central Valley while temperatures are still cool. When these salmon spawn in the late spring and summer, their eggs and juveniles need to be in cooler water than is found in the rivers. They used to spawn in high-elevation mountain streams, where

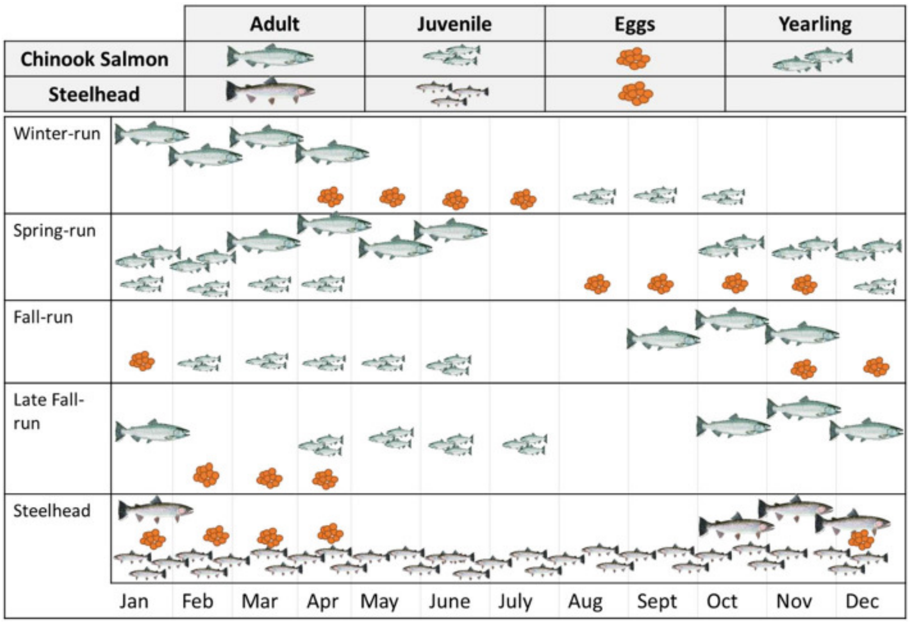

Figure 1

Figure 1

Run timing for salmonids in the Sacramento and San Joaquin Rivers in the California Central Valley. The direction of the fish shows whether they are swimming upstream (headed towards the right) or downstream (headed towards the left). All the adults (larger fish) swim upstream (saltwater to freshwater) while the juveniles (little fish) swim downstream (freshwater to saltwater). Yearlings (medium-sized fish) are juveniles that have spent extra time in freshwater for about a year, so they are really big when they migrate downstream.

water is kept very cool and clean by melting snow. Access to many of these cool mountain streams was blocked by dams (Figure 2). So, now these salmon are trapped!

Winter-run must spawn in less preferred habitat downstream of a dam in the Sacramento River, while spring-run spawn in less than ideal habitats in either the Sacramento or San Joaquin Rivers. If these rivers become too hot during summer, winter-run and spring-run eggs will die. Unfortunately, this has already happened during the long drought of 2012–2016 Without access to naturally cold, high-elevation streams, winter- and spring-run salmon must depend on people to provide them with the cool, clean water they need to survive [2]. Today, winter- and spring-run salmon are less abundant than fall-run salmon because of the dams (Figure 2).

SALMONIDS AT RISK OF EXTINCTION: FISH IN HOT WATER

Salmon must use their natural instincts to navigate the rivers of the Central Valley that connect San Francisco Bay to mountain streams. The key for winter- and spring-run salmon to successfully complete their journey is the water produced by seasonal storms. Seasonal storms allow the rivers and streams to swell and fill their banks. This extra water helps fish get to areas that are out of reach during the dry season, because areas with boulders, steep waterfalls, or other obstacles are flooded allowing fish to migrate upstream. Without this stormwater, salmonids are trapped on the Valley floor where the water is too hot. Sadly, many of these fish die from the high temperatures

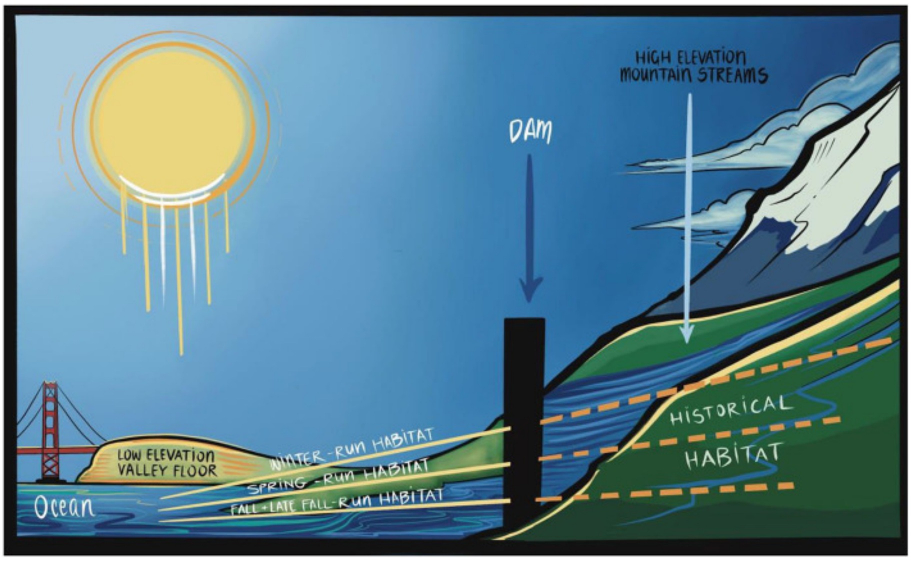

Figure 2

Figure 2

Dams block winter-run and spring-run salmon from reaching the high-elevation mountain streams they evolved to live and spawn in. Currently, all the California Central Valley salmon runs must spawn in low-elevation rivers and streams (Image credit: Stephanie Littlebird Fogel).

before they can return to and spawn in the mountain streams where they were born.

Dams control floods, create electricity, and store water for people living in cities and for crops. But they also block winter- and spring-run salmon and steelhead from reaching the habitats they need to survive [3]. Even a small dam, road crossing, or bridge can create an impassable barrier for a two-foot-long fish. Many dams include special passages for fish to swim up on their own, and sometimes scientists trap fish and move them past the dam in trucks full of water [2]. But the dams in the Central Valley currently do not have any way for fish to get around them, and they block about 90% of winter- and spring-run spawning habitat (Figure 3). As a result, these fish are limited to living only in habitats below dams, which puts their populations at risk of extinction [1].

Dams also negatively change the movement of water, gravel, and wood debris between the mountains and the Central Valley, which fish all depend on. Dams trap the seasonal storm water that helps signal salmonids to swim into the Valley from the ocean and prevent streams from swelling with water, taking away the salmonids' access to the high elevation habitats they once used to survive the hot summer temperatures.

SALMONIDS ARE IMPORTANT FOR THE ENTIRE ECOSYSTEM

From microbes to humans, at least 137 different species depend on salmon. Salmonids are a **keystone species**. Keystone species are like the glue on an art project—without them, the whole thing falls

KEYSTONE SPECIES

A species with a large effect on its ecosystem. The presence or absence of a keystone species affects all the creatures in the ecosystem.

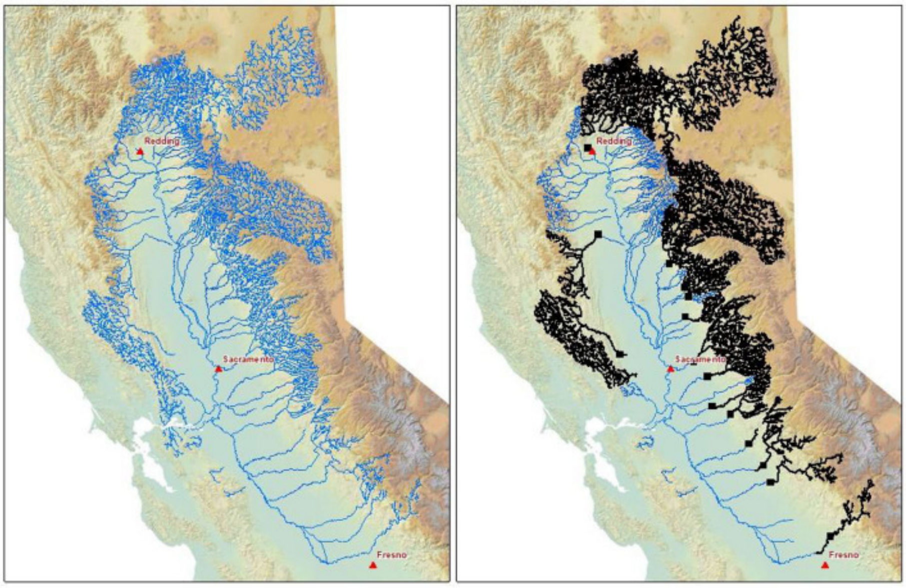

Figure 3

Figure 3

The blue lines represent the habitat that was previously available to salmonids in the California Central Valley. The black lines represent habitat that is now blocked by dams and unavailable to anadromous fish. Dams can alter downstream water flow and temperatures [1]. (Image credit: NOAA Fisheries web story).

apart. An ecosystem will not survive without its keystone species. Salmonids link the rivers to the ocean by collecting ocean nutrients in their bodies as they eat and grow. They bring those nutrients with them when they return to the rivers to reproduce. Unlike salmon, which die after spawning, steelhead can return to spawn multiple times, delivering nutrients again and again. The dead bodies of adult salmonids release their ocean nutrients, enriching the habitats and food chains of the forests and mountains, the way fertilizer enriches a garden, improving soils and helping trees and plants near salmonid streams grow. Areas like the Central Valley have relied on salmonids to deliver these essential nutrients to the landscape for over six million years. Traditional/Indigenous cultures from the Central Valley recognized the role salmon play in the ecosystem and honor them through traditions, making salmon important to past and current residents in the Central Valley. Unfortunately, areas above Central Valley dams have been without those ocean nutrients for almost a century, putting the ecosystem at risk.

HELPING THE SALMON STORY TO CONTINUE

Millions of salmonids once swam through the Central Valley every year, on their journey from the ocean to the mountains. Now, only thousands return, and three of the five Central Valley runs are on the **endangered species** list. Winter-run Chinook salmon only exists in the California Central Valley and is one of the most endangered species in the United States, while spring-run Chinook salmon and steelhead are **threatened**.

ENDANGERED SPECIES

A species at risk of extinction in the very near future. The Endangered Species Act is the law that gives threatened or endangered species and their habitats protections to conserve the species.

THREATENED SPECIES

A species that is likely to become endangered in the foreseeable future (see endangered species).

The National Oceanic and Atmospheric Administration's (NOAA) Fisheries branch of the government is working to conserve and manage coastal and marine ecosystems and resources in the United States. NOAA Fisheries established three criteria that salmonid populations must meet to recover and be taken off the endangered species list [4, 5]. First, salmonid populations must be able to survive changes in annual rainfall caused by climate change. Too much or too little water can be fatal during the wrong time of the year. Second, enough adults must return and spawn each year to support the population of the next generation. Third, there must be multiple salmonid populations in different rivers and streams, so catastrophic events such as diseases or fires don't wipe out the entire species at once [4].

NOAA Fisheries and its partners are working to help Central Valley salmonid populations by finding new places for them to live, helping them move around dams, and looking for other ways to create **resilience** to climate change [2, 4]. You can help, too! Salmonids can be supported through community efforts as simple as picking up trash, planting trees, capturing rainwater for your garden, or saving water during your shower. Our job at NOAA Fisheries is to help scientists and land managers find new ways to help salmonids return home. By bringing fish back to high-elevation streams that are naturally cooler and less populated, we will help these fish survive climate change. Creating resilience involves working together with the people of the Central Valley to use and share water in ways that work for everyone, including the fish. It is everyone's responsibility to reconnect these salmonids to the rivers and streams they spent six million years evolving to inhabit. Afterall, this is their home!

RESILIENCE

The capacity of an ecosystem or organism to respond or adapt to a disturbance by resisting damage and recovering quickly.

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YOUNG REVIEWER

SIGNE, AGE: 10
I live in California and love to learn in 5th grade. Science is my favorite subject and I like experimenting too. Some of my hobbies are dancing, singing, playing instruments, and cooking. My sister is Maya and my kitten is Mabel. I like to play with them both! Bowling is fun and brings me closer to my family. My favorite foods are brownies and vegetarian taco salads. When I grow up, I want to be an actress or teacher.

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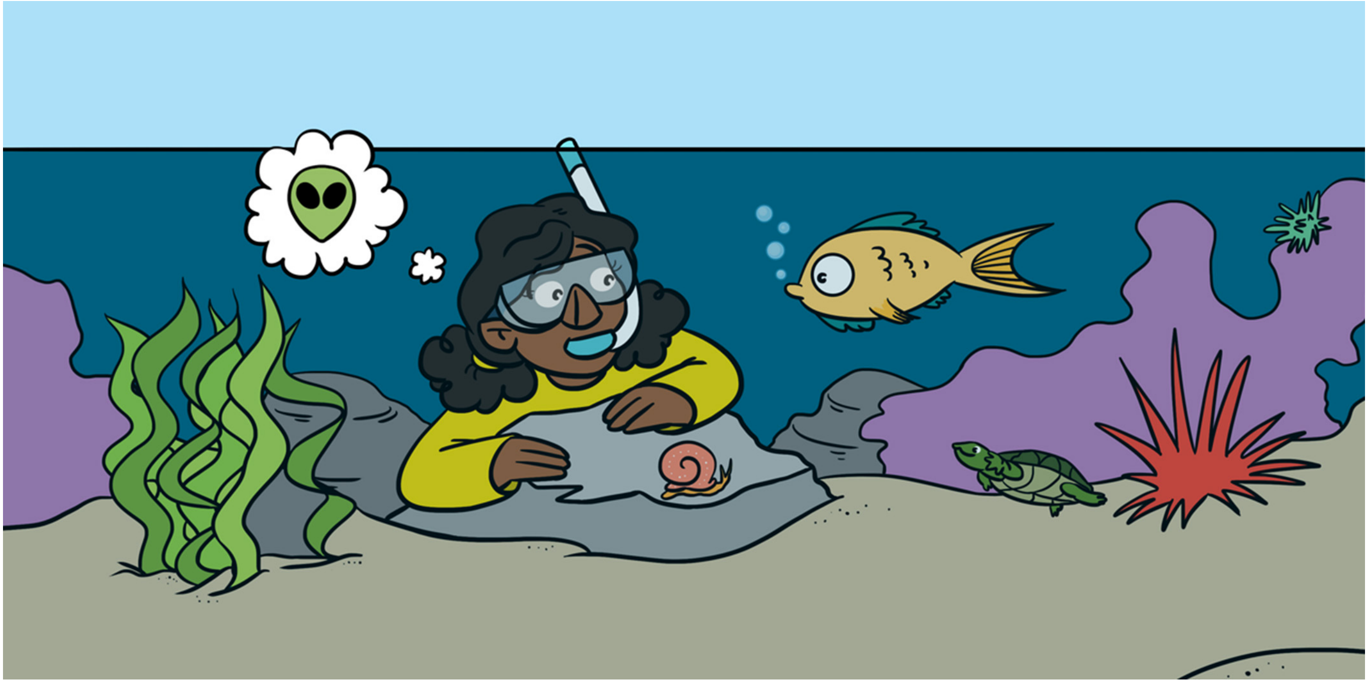

ALIENS FROM AN UNDERWATER WORLD

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YOUNG REVIEWER:

NIKO
AGE: 8

About 3.1 billion people around the world live within 100 km of the coastline. If you are one of those people, then you also live near an estuary. What you probably do not know is that many alien species live in this underwater world, and we are not talking about extraterrestrial species from outer space. Are you scared? Well, do not be! These alien species are from planet Earth. In this article, we will tell you what alien species are, why scientists study them, how any species may become an alien, and how a few alien species may become an invasive species. You will also learn how you can help scientists find and track alien species, and how to defeat them. Along the way, we will give examples of alien species living in the San Francisco Estuary in North America, a paradise for hundreds of alien species.

WHAT ARE ALIEN SPECIES?

When someone talks about aliens we immediately think about extraterrestrial life. But you can probably encounter aliens right outside your home, because alien species are all around us! Look up and you may see the Eurasian collared dove flying above you. Under your feet, nightcrawlers may be squeezing their way through the soil toward their next meal. Right in front of your eyes, you may see full-grown Australian acacia trees that are easy to notice because of their yellow flowers. Aliens like the common carp are present underwater, swimming in the rivers alongside us.

If these are not aliens from outer space, what are they? **Alien species** are species that live in nature but far away from their natural **distribution range**. Species that live in their natural distribution range, the area where they evolved and adapted for thousands of years, are called **native species** or indigenous species. For a species to be called alien, it must have crossed geographical barriers like mountains, oceans, or deserts, with the help of humans. Some alien species were moved to new areas on purpose, but often their introduction into a new environment was accidental.

ALIEN SPECIES

Species that live in nature but far away from their natural distribution range. Alien species cross geographical barriers like mountains, oceans, or deserts, with the help of humans.

DISTRIBUTION RANGE

The regions occupied by a species.

NATIVE SPECIES

Also called an indigenous species, a species that is present in the region where it has evolved and lived for thousands of years.

WHY SHOULD SCIENTISTS STUDY ALIEN SPECIES?

There are at least four important reasons for scientists to study alien species. The most important reason is to learn how to avoid introducing alien species into new **ecosystems**. Second, it is important to know if an alien species may harm the native species. For example, after the overbite clam (Figure 1I) was introduced into the San Francisco Estuary, the number of native shrimps and anchovies decreased. This happened because the overbite clam made the food of anchovies and shrimps less available [1]. Third, we need to learn how to best eliminate alien species, especially those that harm native species. Last, we need to know if an alien species may damage man-made structures. For example, in the San Francisco Estuary, a naval shipworm ate wooden wharves and ferry slips, which caused over $825 million USD in losses during the first 7 years of its invasion [2].

ECOSYSTEM

An area with distinctive characteristics where animals, plants, and other organisms interact with each other and the environment. Estuaries, deserts, and forests are examples of ecosystems.

ALIENS IN THE ESTUARY

The San Francisco Estuary is the biggest in California, United States, and home to thousands of plant and animal species. Some of these species came from distant regions. The first alien species identified in the San Francisco Estuary was the bay barnacle, found in samples collected in 1853 (Figure 1D). By the late 1990s, scientists estimated that four new alien species were calling the Estuary their new home every single year [2]. Two of the most recent alien species are a small fish called bluefin killifish, first detected in 2017, and a semiaquatic rodent called nutria, first detected in 2018 (Figures 2A,F) [3, 4].

The famous western mosquitofish was often introduced intentionally to eat the larvae of annoying mosquitoes. The first time it was found

Figure 1

Figure 1

Some of the alien species present in the San Francisco Estuary and adjacent ecosystems. **(A)** Brazilian waterweed; **(B)** Atlantic pileworm; **(C)** sulpher boring sponge; **(D)** bay barnacle; **(E)** eastern mudsnail; **(F)** eastern oyster drill; **(G)** eastern white slippersnail; **(H)** amethyst gem clam; **(I)** overbite clam; **(J)** common Atlantic soft-shelled clam; **(K)** Japanese clam; **(L)** convex slippersnail; **(M)** Pacific oyster; **(N)** eastern oyster; **(O)** Japanese mussel (Photo credits: BioDiversity4All.org).

near the San Francisco Estuary was in 1964–1965, and is now common around the Estuary and Delta [2] (Figure 2C). In tropical regions, a disease called malaria is passed on to humans by mosquitoes, so introducing mosquitofish into rivers, lagoons, and ponds decreases the number of adult mosquitoes and the chances of people getting sick. Species that are good for fishing may also be intentionally introduced. That is why you can find striped bass and American shad in the Estuary (Figures 2D,E).

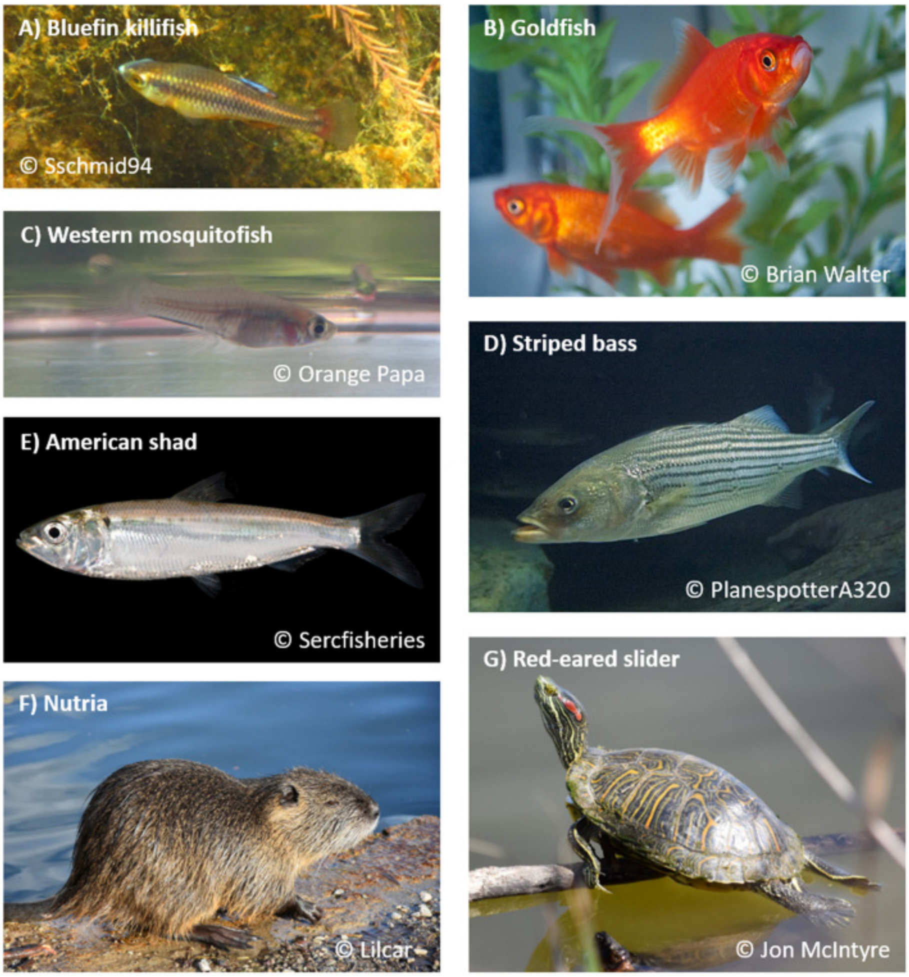

Figure 2

Figure 2

Some of the vertebrate alien species present in the San Francisco Estuary and adjacent ecosystems. **(A)** Bluefin killifish; **(B)** goldfish; **(C)** western mosquitofish; **(D)** striped bass; **(E)** American shad; **(F)** nutria; **(G)** red-eared slider (Photo credits: BioDiversity4All.org).

Intentional introductions may also result in unintentional introductions. The Pacific oyster and eastern oyster were introduced intentionally into the San Francisco Estuary in the late 1930s and 1800s, respectively (Figures 1M,N). Although these species did not successfully establish themselves in the Estuary, scientists noticed that many new alien species appeared around the same time. Some of these aliens hitchhiked attached to the oysters' shells or to the hulls of ships that brought the oysters, and some arrived in the **ballast water** of these ships. Several additional examples are shown in Figure 1.

BALLAST WATER

Water carried inside the hulls of ships to balance them. When ships are loading cargo, ballast water is dumped to keep the ship from carrying too much weight.

Ballast water is one of the most common ways to unintentionally introduce alien species (Figure 3). Big transoceanic ships carry ballast water in their hulls to give them stability as they travel the ocean. This water can be full of living creatures that are ready to find a new home. When the ships take on cargo, they often dump their ballast water in ports, which can introduce alien species. In 2000, ships coming from overseas to the San Francisco Estuary dumped enough water to fill 840 Olympic swimming pools [5]. That is a lot of water… and potentially a lot of aliens!

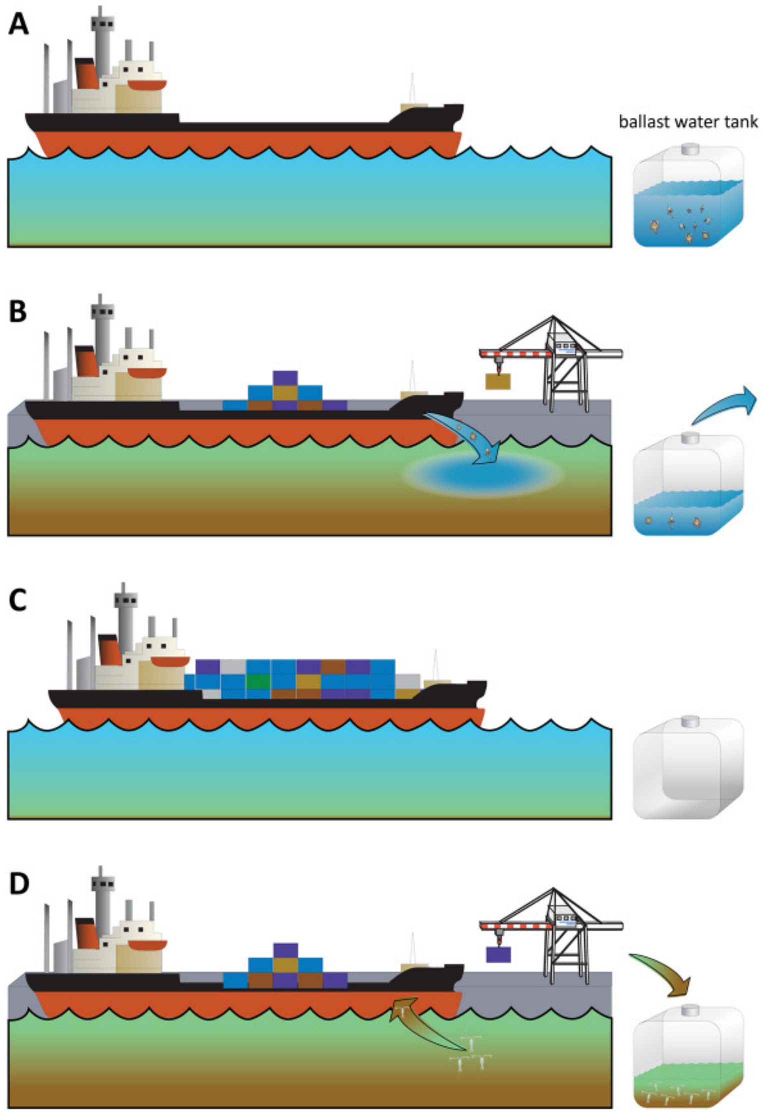

Figure 3

Figure 3

Ballast water can transport alien species. **(A)** Full ballast water tanks help to stabilize a ship when the cargo hull is empty. This water may contain plant and animal species. **(B)** Ships discharge ballast water, and any alien species it contains, when they are in port loading cargo. **(C)** Ballast water tanks are empty when the ship is loaded with cargo. **(D)** New water—and a new set of organisms—is pumped into the ballast water tanks when the cargo is unloaded.

Alien species are also frequently introduced into new ecosystems from people's homes or aquariums. Some alien species were once someone's favorite pet, like goldfish and red-eared sliders (Figures 2B,G), or may have been used to decorate an aquarium, like the Brazilian waterweed (Figure 1A).

SOME ALIEN SPECIES BECOME INVASIVE

When alien species arrive in a new place, some of them find the new environment too harsh, and they eventually die. However, other species find the environment to their liking and spread all over the place. When an alien species spreads widely in its new environment, often causing negative impacts on native species, it is called an **invasive species**.

INVASIVE SPECIES

A species that finds a new place to live, away from its native area, and increases in number, sometimes causing negative impacts on native species and the ecosystem.

There are several reasons why some alien species become invasive. First, many invasive species can tolerate harsh environments, so they can live in places that are polluted or where the environmental conditions change often. These places tend to have few other organisms living there, which allows the alien species to settle in more easily and start a big family. Other alien species thrive because the parasites that affected them in their native environment are not present in their new home. Parasites delay the growth of any species, so if an alien species does not have parasites, each individual of that species will be healthier and able to reproduce more. Also, alien species often have fewer (or no) enemies in their new homes, because the native predators do not recognize the aliens as food. Over time, however, predators may learn that the alien species can be a good meal, which can halt its spread. Finally, many alien species become invasive species because they can reproduce in large numbers. So, when something bad happens, the alien species can recover more quickly than the native species.

HELP SCIENTISTS DISCOVER ALIEN SPECIES

Biologists (scientists who study living things) have come to realize that they can rely on farmers and fishers to help them understand how local ecosystems function and how the plants and animals in an area change over time. Other people with an interest in nature can also help biologists. Some biologists actively recruit and train people to help them with their work. These people become **citizen scientists** and help biologists gather precious information from a larger area and in a shorter time than the scientists could do on their own. Without the help of citizen scientists, it might take biologists years to do the same work. For example, citizen scientists are helping marine biologists to find alien species in Portugal and to discover how fast the invasive Atlantic blue crab is spreading [6].

CITIZEN SCIENTIST

Any person that helps professional scientists to complete a research study on a subject of their interest. There are citizen science projects on many topics, like biology, astronomy, or archaeology.

FIGHTING ALIENS

Fighting alien species is expensive because they are difficult to eliminate, especially those hidden underwater. Strategies like fishing an invasive fish, dredging the sand to pick invasive clams, diving to pluck invasive algae, or scraping rocks to collect invasive mussels are never completely successful. These actions must be done over many years, and if a handful of aliens are left unharmed, the population will often bounce back within a few years. The best strategy to fight alien species is to avoid their introduction in the first place. To avoid the introduction of new species via ballast water, laws were created in 2017 stating that transoceanic ships can no longer dump ballast water when they arrive at a port; they must dump it in the ocean, far from the coast. We can all avoid introducing alien species by not releasing pet fish, turtles, or aquarium plants into nature. We can also be on the lookout for alien species in our areas, so that we can eliminate them before they spread and become invasive. Maybe you can become a citizen scientist, help biologists look for alien species, and help to keep these species from spreading.

Now that you know so much about alien species and how to fight them, share your knowledge with your friends and family. Ask scientists if they need help finding alien species and become a citizen scientist. You can find projects that you may like on many websites, like https://www.zooniverse.org, https://scistarter.org, https://science.nasa.gov/citizenscience, https://www.nps.gov/subjects/citizenscience/be-a-citizen-scientist.htm, or https://www.nationalgeographic.org/idea/citizen-science-projects/. Small actions may lead to big changes, and you can be the one to spark the change in your neighborhood! We must all work together to protect our precious planet from the dangers posed by alien species.

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YOUNG REVIEWER

NIKO, AGE: 8
I love Pokemon and soccer. I love writing about animals. My favorite books are about dinosaurs and predators.

AUTHORS

PEDRO MORAIS
My passion for marine biology began when I was 7 years old. I went on vacation with my parents and sister to a lovely beach in southern Portugal. There, I spent all the time I could in the tide pools searching for fishes, crabs, shrimps, and anemones. I have studied all kinds of aquatic organisms (bacteria, microscopic algae, jellyfish, clams, crabs, birds, fish, and even whales and dolphins) from the deep ocean to shallow lagoons, estuaries, rivers, lakes, and streams. During my free time, I enjoy dancing tango, taking photographs, woodworking, fixing and restoring old things, and researching my ancestry. *pmorais@ualg.pt

JOÃO ENCARNAÇÃO
For as long as I remember, the ocean has been my backyard and my playground. At first I fished and surfed, and then I started to look into the underwater world with more attention. This happened during my first SCUBA diving course in 2009. At the same time, underwater photography became another big passion of mine!

Meanwhile, I completed a degree in marine biology so that I could identify all the fish species I saw underwater. I have studied the impacts of dams on estuarine species and the effects of natural freshwater springs on marine coastal biodiversity. Now, I am doing a Ph.D. and studying aquatic invasive species in Southern Portugal.

MARIA ALEXANDRA TEODÓSIO

I was born in a small town in southern Portugal, surrounded by salt marshes and the Guadiana Estuary. I learned to like the smell and dark color of the estuary, and discovered that there are amazing treasures hidden underwater. When I was a teenager, I followed my father to rescue a sunken boat in the estuary. Then, I followed my waterway, and as a river always finds the sea, I went to the University of Algarve to study marine biology. For the last 30 years, I have been a professor and scientist at this University. I like to teach and study estuarine ecology and biological oceanography. My specific research interests include studying the nutritional condition of marine organisms and how global change impacts marine biodiversity. For fun, I like to paint everything, from furniture to walls and, sometimes, even "real paintings."

ESTER DIAS

I am a researcher at the Estuarine Ecology and Biological Invasions Research Group (CIIMAR-University of Porto, Portugal). As a child, I was curious about how animals behave, what they eat, and why they need to migrate long distances to reproduce. So, becoming a biologist was my chance to find the answer to these questions. So far, I have studied small aquatic animals called zooplankton (some only 1 mm long), clams, aquatic birds, fish, and even marine mammals. Currently, I study the migrations of fish, the impacts of biological invasions, and what is on the menu of each aquatic species.

BIODIVERSITY
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CRIME SCENE SAN FRANCISCO: WHO IS RESPONSIBLE FOR THE DISAPPEARANCE OF DELTA SMELT?

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California Department of Water Resources, West Sacramento, CA, United States

YOUNG REVIEWERS:


HUGO
AGE: 9


ITZAMNÁ
AGE: 8

Delta smelt are becoming harder and harder to find in the San Francisco Estuary. Some of the suspects in their disappearance are invasive fish species that were introduced from other places into the Estuary. These invasive fish can impact their new habitat by eating the native species that were originally there. However, it is hard to understand what the invasive fish are eating. We found that we can use the DNA in the stomachs of invasive fish to figure out what they have eaten. We caught a common invasive fish in the Estuary, called the Mississippi silverside, and analyzed the DNA from their stomachs to see if it matched delta smelt DNA. We discovered that some Mississippi silversides had delta smelt DNA in their stomachs! We therefore believe that Mississippi silversides are one of the culprits causing the disappearance of delta smelt.

THE SCENE OF THE CRIME

ESTUARY

The end portion where one or more freshwater rivers flow into the saltier ocean.

INVASIVE SPECIES

A species that has been moved from its original location and introduced into a new environment where it competes for resources with the species that normally live there.

An **estuary** is the final section of one or more freshwater rivers before they meet the salty ocean. This mixing of salty and fresh water in estuaries creates unique environments, with varying degrees of saltiness, in which plants and animals can live. The San Francisco Estuary is the largest estuary on the west coast of the United States and it may contain more **invasive species** than most estuaries. Invasive species are species that have arrived in an environment from somewhere else and tend to take over their new environments [1]. While native species were once widespread, the Estuary is now home to many invasive species of fish, plants, clams, jellyfish, and plankton from all over the world. In the last few decades, tragedy has struck the Estuary. A once abundant and highly sensitive native fish species, the delta smelt, is mysteriously disappearing at an alarming rate [2]. Many years ago, millions of delta smelt swam freely throughout the delta region of the Estuary, a maze of channels formed where the Sacramento and San Joaquin rivers meet. In recent years, delta smelt have been hard to find. Scientists are on a mission to solve the case of the vanishing delta smelt.

THE VICTIM'S PROFILE

Delta smelt are a small species of fish that only live in the Estuary and nowhere else in the world. They are silver and gray in color, grow to about 5–7 cm as adults (Figure 1A), and smell like cucumbers. Delta smelt can live in aquatic habitats with varying levels of saltiness. This makes the Estuary the perfect home for them [2]. Delta smelt only live about 1–2 years and they are sensitive to environmental changes like drought and warm water temperature. Drought and warm water temperature are occurring more commonly in California due to climate change [3] and these conditions reduce the ability of the delta smelt to survive and to lay eggs [4]. The numbers of delta smelt have declined so much that they are now protected under both the United States Federal Endangered Species Act and the State of California Endangered Species Act [5].

THE SUSPECTS

Based on information scientists have collected, there are multiple suspects that could be responsible for the disappearance of delta smelt. Three of the primary suspects include: (1) invasive species that outcompete or eat delta smelt; (2) loss of or changes to the physical water bodies they inhabit that make it difficult for delta smelt to live in the estuary; and (3) extreme changes in environmental conditions, such as water temperature, salinity, and muddiness of the water. The environment in the Estuary is complex and has changed over time. Therefore, it is likely that all three of these suspects, and possibly

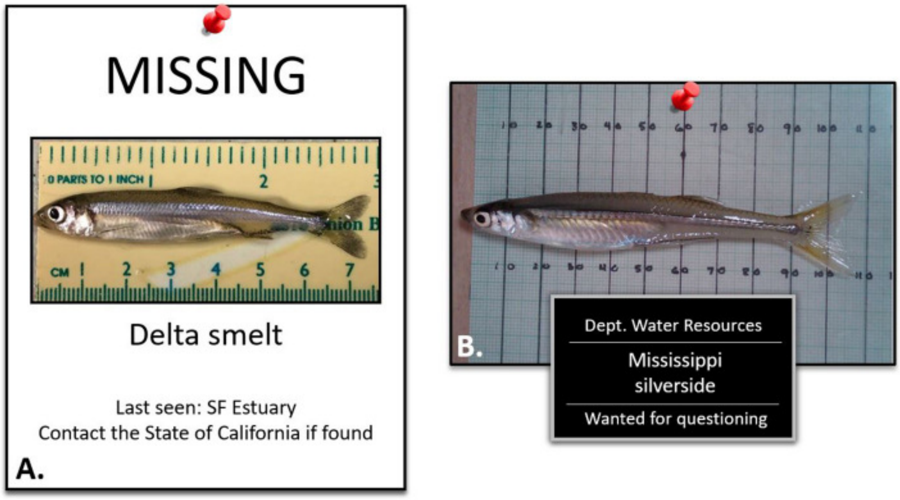

Figure 1

Figure 1

(A) The missing delta smelt and **(B)** the suspected Mississippi silverside.

many others, have contributed to the disappearance of delta smelt. This investigation will focus on the first suspect: invasive species that outcompete or eat delta smelt.

INVESTIGATION OF THE CRIME SCENE

First, we wanted to know which invasive species to question about the disappearing delta smelt. We quickly began to suspect the Mississippi silverside, an invasive fish whose introduction to the Estuary happened around the same time as the disappearance of delta smelt (Figure 1B). Oddly enough, delta smelt and Mississippi silversides are very similar in their appearance, size, habitat preference, and eating habits. However, since an adult fish cannot eat another fish of the same size, we think that the adult Mississippi silverside might be eating delta smelt when they are small **larval** fish, or when they are still eggs.

LARVAL

An early form of any animal that sometimes looks very different from the juvenile or adult stages.

We needed a method to test if Mississippi silversides eat delta smelt in the Estuary. But how could the unidentifiable, digested stomach contents of Mississippi silversides tell us what they ate? One way to find or detect a species is to test for the presence of its DNA. DNA is the unique set of genetic codes that all living creatures have. Like all good detectives, we tried to solve our crime by finding evidence directly linking the suspect to the victim, such as the presence of the victim's DNA inside the suspect's stomach. To do this, we collected Mississippi silversides from two locations where delta smelt are known to live, in nearshore and mid-channel environments of the Sacramento River Deep Water Ship Channel (Figure 2). We then looked for delta smelt DNA in the stomachs of Mississippi silversides.

We collected Mississippi silversides in the Sacramento River Deep Water Ship Channel during early April, which is also the peak time when

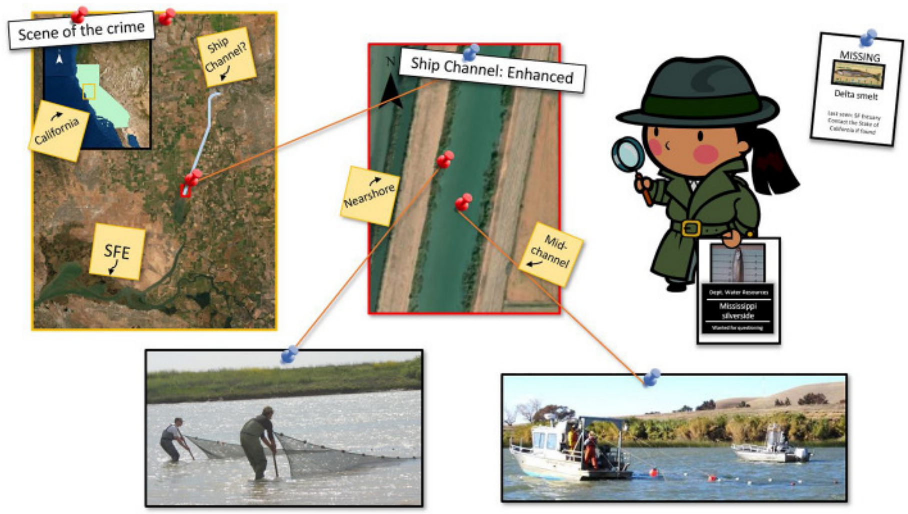

Figure 2

Figure 2

The scene of the crime, where we suspect Mississippi silversides may be eating delta smelt. If we zoom in on the state of California, USA, we can see the Delta in the upper part of the San Francisco Estuary (SFE) in the yellow-outlined box. If we zoom in further on the red box in the estuary, we see a satellite image of the Sacramento River Deep Water Ship Channel. Mississippi silversides were collected from two locations in the Ship Channel, using two different methods: nearshore, using a beach seine, and mid-channel, using a trawl from a boat (Trawl photo credit: California Department of Fish and Wildlife).

TRAWL

A method to catch fish that involves dragging a large net in the water behind a boat.

BEACH SEINE

A method to catch fish which uses a net strung between two poles that is dragged along the bottom of a water body.

FLUOROPHORE

A light attached to a DNA assay that glows when it finds a DNA match, alerting us to the presence of the DNA of the species we are looking for.

delta smelt lay their eggs. Fish in the mid-channel were captured using a **trawl**, which is a net dragged behind a boat. Nearshore fish were collected using a **beach seine**, which involves two people dragging a net along the bottom near the shore (Figure 2). The more Mississippi silversides that we captured, the greater the chance of detecting delta smelt DNA in their stomachs, and the stronger the evidence would be. We removed the stomach contents from all the Mississippi silversides we caught and extracted the DNA of the food in their stomachs. We used a method that breaks open the cells of the Mississippi silverside food so that we could release the DNA inside (Figure 3A).

We then used a DNA assay that could alert us to the presence of delta smelt DNA in the stomach contents of Mississippi silverside [6]. This assay is designed to match up, like a puzzle piece, with the unique DNA sequence of a delta smelt (Figure 3B). When the DNA in the assay matches with delta smelt DNA in the sample, a little fluorescent light on the assay, called a **fluorophore**, glows to indicate that a match was found (Figure 3C). This means that if delta smelt DNA is present in the stomach sample, there will be a fluorescent signal. The absence of a fluorescent signal tells us that delta smelt DNA was not in the stomach of the Mississippi silversides, or was not eaten recently enough to be detected.

INVESTIGATION RESULTS

The investigators brought a total of 651 Mississippi silversides into the laboratory for intensive questioning (in this case, stomach dissections) related to the disappearance of delta smelt. Of the 651 suspects, 614 of them were collected from the nearshore habitat and 37 were collected from the mid-channel habitat. The suspects of the nearshore habitat were found innocent, having no detectable delta smelt DNA in their

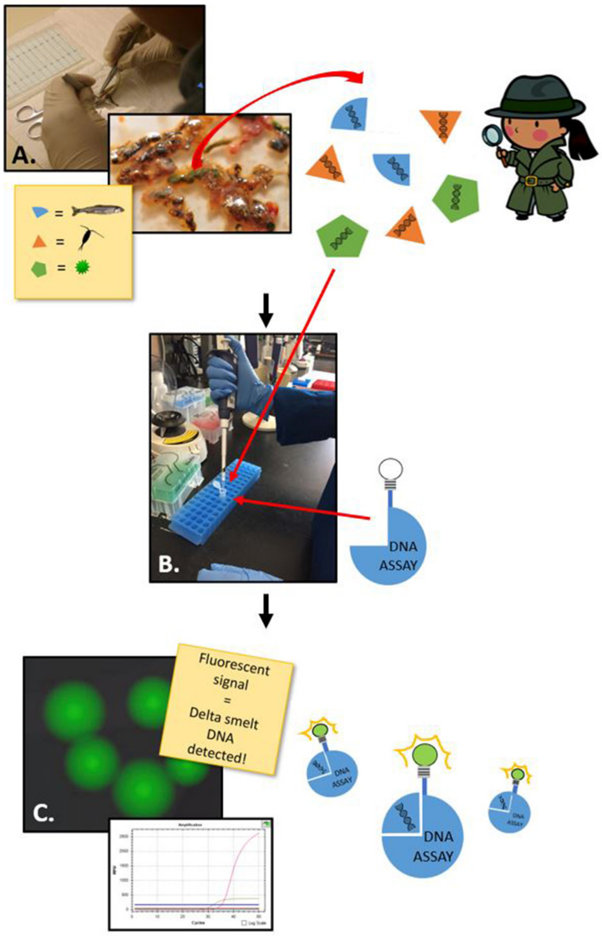

Figure 3

Figure 3

(A) Stomachs were removed from Mississippi silversides and DNA was extracted from the stomach contents. **(B)** Extracted DNA was tested using the delta smelt DNA assay. **(C)** If delta smelt DNA was present, the assay would bind to the DNA and the fluorophore in the assay would light up. (Fluorescence photo credit: New England Biolabs).

stomachs: all 614 suspects tested negative. For the suspects in the middle of the channel, almost half (41%) tested positive for delta smelt DNA: 15 out of 37 Mississippi silversides were guilty and charged with eating delta smelt.

CASE STILL OPEN

The DNA results showed that Mississippi silversides do in fact eat smaller, younger delta smelt and could be a possible reason for the disappearance of this species. Because all Mississippi silversides containing delta smelt DNA came from the mid-channel of the Sacramento River Deep Water Ship Channel, we guessed that larval delta smelt prefer to spend their time in the middle of the channel. Delta smelt prefer to live in specific conditions, with cool temperatures and muddier water, which they may be more likely to find in the middle of the channel. Alternatively, it is possible the Mississippi silversides eat different prey in different parts of the channel. Mississippi silversides are also known to move to different areas during the day, to follow prey. It is possible the Mississippi silversides in the nearshore beach seine samples had not yet moved into the mid-channel to eat delta smelt. Importantly, DNA is only in the stomach until the predator finishes digesting and processing the meal. This means that delta smelt DNA would not be detected if a Mississippi silverside had eaten a delta smelt and then pooped it out before it was caught.

More detective work is needed to fully solve the mystery of the missing delta smelt. Researchers could look at how environmental factors affect when Mississippi silversides eat delta smelt. They could also use the DNA assay to see if other fish species are preying on delta smelt. Using DNA detection has allowed scientists to better understand which foods the fish in the estuary are eating and how diet preferences impact the abundance of native species. However, there are plenty of other major problems in the estuary that may contribute to the disappearance of delta smelt, so this important investigation will be long and complicated.

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ORIGINAL SOURCE ARTICLE

Baerwald, M. R., Schreier, B. M., Schumer, G., and May, B. 2012. Detection of threatened delta smelt in the gut contents of the invasive Mississippi silverside in the San Francisco Estuary using TaqMan assays. *Trans Am Fish Soc.* 141:1600–07. doi: 10.1080/00028487.2012.717521

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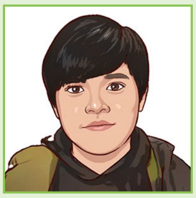

HUGO, AGE: 9

My name is Hugo, I am 9 years old and I am from Mexico City. My favorite hobbies are: playing video games, building with legos, listening music, and playing soccer. My favorite soccer team is "FC Barcelona" and I love to play goalkeeper. I enjoy drawing and seeing monuments, one of my biggest dreams is to travel around the world to see the most important monuments and buildings of each city. When I grow up I would like to be an architect or a professional soccer goalkeeper.

ITZAMNÁ, AGE: 8

Hi there! My name is Itzamná, it is a Mayan name. I love dinosaurs and e-games and I spend a lot of time playing Roblox or Minecraft. I have been camping since before I could walk, so I think I am a nature lover. I like science and enjoy each time I participate in scientific events for kids because I love to do experiments with plants' or animals' DNA.

AUTHORS

MALLORY E. BEDWELL

I am interested in using genetic techniques to help with management and conservation of species. In the past, I have studied how different species of amphibians have evolved. Most recently, I did research on how DNA released into the environment (called eDNA) from yellow-legged frogs can best be sampled to detect them in streams and lakes. At the California Department of Water Resources, I help collect samples that look at the overall state of the Yolo Bypass, including water quality, zooplankton, and fish. I plan on using eDNA monitoring techniques in the future to look for rare fish and to better understand zooplankton communities.
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CRAIG STUART

As a fish and wildlife scientific aid for the California Department of Water Resources, I have worked in Sacramento, CA researching aquatic ecology in the San Joaquin-Sacramento River Delta, specifically the Yolo Bypass floodplain. My work has mostly comprised of investigating the food web in the Yolo Bypass and understanding seasonal presence and abundance of native and non-native fish species, including Chinook salmon, delta smelt, and sturgeon. My interests include the conservation and habitat restoration of Chinook salmon and other fish species native to California. I began my Master of Environmental Science and Management degree from the University of California, Santa Barbara in fall of 2020.

MELINDA R. BAERWALD

Two things I feel passionate about are the conservation of threatened species and learning new things about our world through science. I am lucky because, in my job as an environmental program manager for the California Department of Water Resources, I get to do both! Most of my work is done as part of a team made up of scientists with different skill sets. I like to use genetic tools to understand aquatic species diversity, detect species even when you can not see them (using environmental DNA), and link important traits (migration, disease resistance, etc.) to underlying genetic variation.

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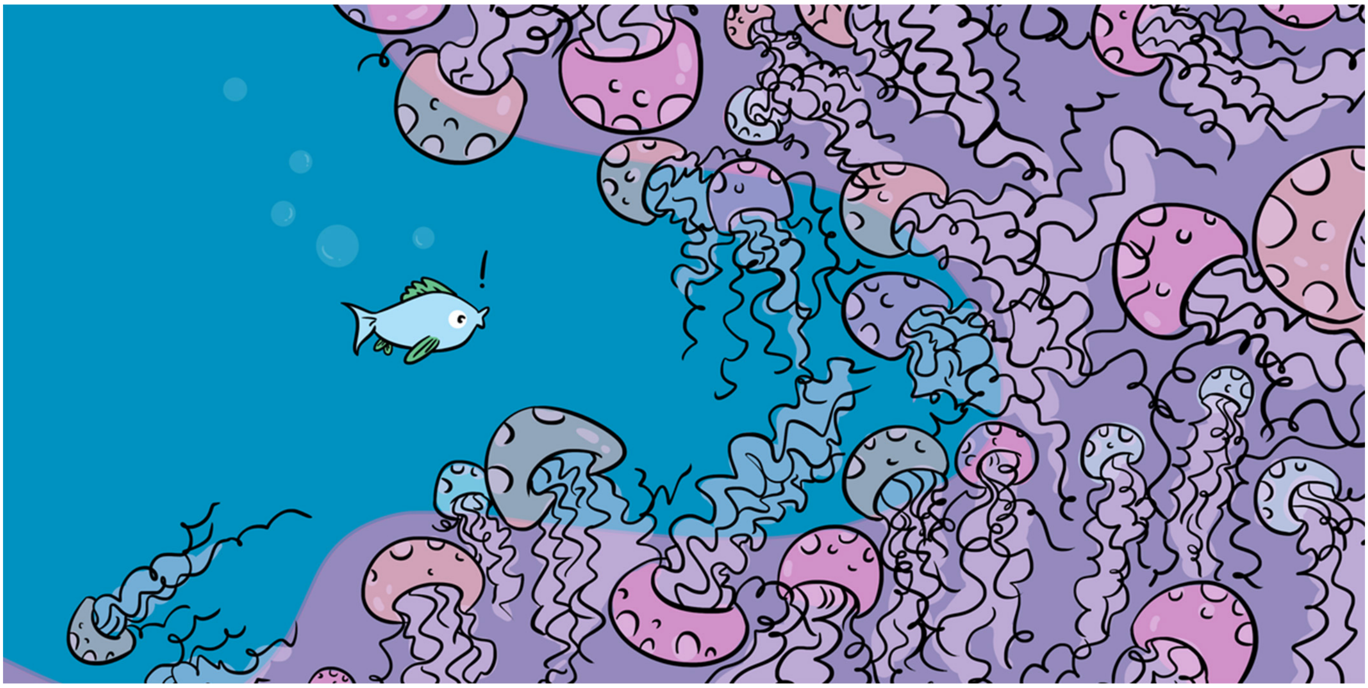

BLACK SEA JELLYFISH: SHOCKING NEWCOMERS TO SUISUN MARSH

Caroline L. Newell[1*], *John R. Durand*[1,2], *Mariah H. Meek*[3] and *Peter B. Moyle*[1,2]

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YOUNG REVIEWERS:

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AGES: 10–12

Black Sea jellyfish love to travel. Far from their original home in the Black Sea of Southeastern Europe, Black Sea jellyfish have come to the San Francisco Estuary. Since these jellyfish first started regularly appearing in fishing nets in the early 1980s, scientists have been finding more and more of them in the San Francisco Estuary. Over the past 40 years, our lab has tracked the numbers of Black Sea jellyfish in a part of the Estuary called the Suisun Marsh. Over this time, we have observed increasing amounts of jellies, with the highest amount ever recorded caught in 2019. What does this mean for the San Francisco Estuary and its other current residents? This is a question we will explore in this article.

INTRODUCING THE BLACK SEA JELLYFISH

Jellyfish on display in aquariums are charming. They casually swim around their tanks, awing on-lookers with their peaceful calmness.

Figure 1

Figure 1

A live Black Sea jellyfish resting on the bottom of a tank. Its many tentacles move around, searching for something to eat (Photo credit: Dave (Gio) Giordano).

Jellyfish are beautiful and mysterious animals with big bell-shaped heads and long hair-like tentacles. Jellyfish do not just live in tanks though, they live out in the wild, too! We catch jellyfish in our nets, sometimes by the hundreds, when we are sampling fish in the San Francisco Estuary in California, United States, where freshwater from streams and rivers meets the salty Pacific Ocean water. The "jellies," as we call them, look like soft, clear blobs of jelly, and are often only a little bigger than a golf ball in size (Figure 1). The jellies are not fish—they are **invertebrates** that drift with water currents.

INVERTEBRATE

Animal without vertebrae (spine bones).

Black Sea jellyfish are a relatively new, non-native species in the Estuary, and their role in the Estuary has only recently been studied. Their name is a give-away to their native home: they were once found only in the Black Sea, in Southern Europe. How does a weak-swimming invertebrate end up over 9,700 km (6,000 miles) away from home? They hitch a ride in the water that cargo ships take on in far-away ports to balance them as they cross the world's oceans. When that water is released near the Estuary, the hitch-hiking creatures are released too, and the wind and tide move the Black Sea jellyfish upstream.

MARSH

A wet and muddy grass-filled habitat near a river or coastline. Marshes are home to a lot of animals—birds, fishes, mammals, and more!

Suisun Marsh is one spot in the upper Estuary where these jellyfish are doing especially well. The **marsh** provides a safe refuge for many species. Since 1980, our team of researchers at University of California, Davis has been looking at what lives in the Estuary's waters. Every month, we go to the Estuary to sample the animals that live there. We use nets called **trawls**, which are dragged behind a boat. Black Sea jellyfish first appeared in the trawls in the early 1980s. Since then, there has been an increase in Black Sea jellyfish populations in the Estuary (Figure 2).

TRAWL

A method of collecting animals from the water by dragging a net behind a boat.

WHY ARE SCIENTISTS ALARMED BY SMALL JELLYFISH?

Black Sea jellyfish look small and fragile, but they have four traits that may help them to cause a lot of damage to the Estuary. First, they have

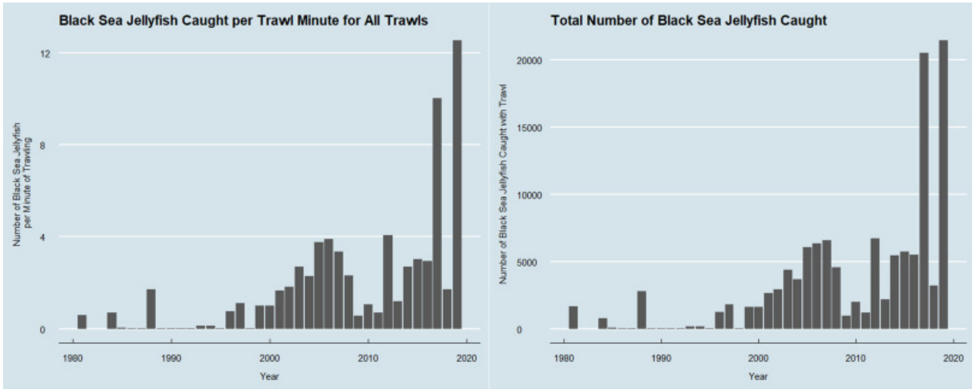

Figure 2

Figure 2

(A) The number of Black Sea jellyfish caught per minute of trawling, in Suisun marsh. **(B)** Total number of Black Sea jellyfish caught in these trawls. You can see that, ever since 1980, there have been increasing numbers of jellyfish in the Suisun Marsh, with a record 21,478 individuals caught in 2019.

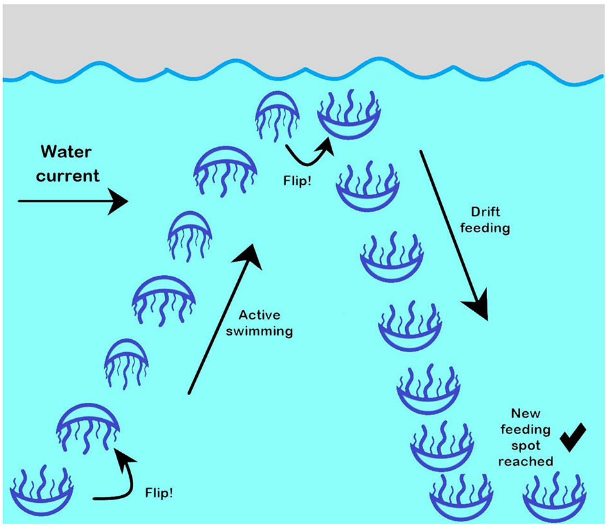

Figure 3

Figure 3

Swimming behavior of a Black Sea jellyfish. Jellyfish swim to the surface of the water, flip over, and sink slowly to the bottom with their tentacles stretched out, searching for food as they descend. Once the jellyfish reach the bottom, they stay upside-down and twitch the ends of their tentacles, likely trying to lure bottom-dwelling zooplankton into their lethal trap (Image based on Wintzer et al. [1]).

an effective hunting strategy that allows them to capture prey from the top to the bottom of the water. Most of their time is spent on the bottom, where they sit upside-down, wriggling their tentacles about and grasping for food. Every so often, they flip themselves bell-side up and swim to the surface. Once they reach the surface, they flip themselves upside-down again and float down to a new sitting spot [1]. As they go up and down, water currents carry them to new locations, allowing them to spread and find new patches of food (Figure 3).

Second, the bell-shaped bodies of Black Sea jellyfish are lined with hundreds of stinging tentacles. They use these stingers to catch and kill their prey. Scientists and managers are concerned that small fish in the Estuary are being killed by these stingers, and that the jellyfish are consuming small invertebrates that fish rely upon for food.

Third, Black Sea jellyfish quickly reproduce, thanks to a unique style of reproduction. Their life cycle is divided in two parts. Jellyfish in the adult phase are called **medusae**, and they can swim freely in the water. When jellyfish are young, they are called **polyps**. The polyps cannot move and live attached to hard surfaces, such as rocks, docks, ropes, and even empty shells. As polyps develop, they can release dozens or hundreds of small medusae.

MEDUSA

The adult stage of a jellyfish's life cycle. Medusa swim freely through water.

POLYP

The juvenile stage of a jellyfish's life cycle. Polyps do not move and are attached to hard surfaces underwater.

Fourth, Black Sea jellyfish do not have natural predators in the Estuary. Consequently, since they eat a lot, reproduce quickly and in great numbers, and have no natural enemies, the number of Black Sea jellyfish can increase massively. Scientists call this rapid population increase a **bloom**. Blooms happen when water conditions favor the jellyfish, usually during the summer and fall when the water is warm and salty [2, 3]. At times, the jellyfish are so densely packed in the water that it may be hard for small fish and invertebrates to avoid getting stung by their tentacles. Together, these four traits make the jellyfish a potential threat to the San Francisco Estuary ecosystem.

BLOOM

A sudden large increase in numbers of jellyfish.

A STUDY OF BLACK SEA JELLYFISH IN THE SAN FRANCISCO ESTUARY

To evaluate whether the four traits of Black Sea jellyfish described above truly have a negative impact on fish in the San Francisco Estuary, our team studied the population size and behaviors of Black Sea jellyfish in Suisun Marsh. We asked three questions: (1) What do Black Sea jellyfish eat? (2) Do jellyfish eat larval (baby) fish? And, (3) Do jellyfish compete with fishes for food? [1].

To answer the first two questions, we examined the diets of Black Sea jellyfish in Suisun Marsh, by catching jellyfish in nets and using microscopes to look at what was in their stomachs. We found that jellyfish mostly feed on tiny **zooplankton** with hard shells, called **amphipods**. We found that Black Sea jellyfish *do* eat larval fish, but they were not common in the diet of jellies: only 4% of jellies' overall diet was larval fish. But this does not mean that larval fish are necessarily safe from the jellies—the lack of predation on larval fishes might simply be due to timing. When the jellyfish bloom and are on the hunt, most fishes have passed their larval stage. Many fishes hatch early in the spring and are too big for the jellyfish to kill by the time the summer blooms come [1].

ZOOPLANKTON

Small aquatic invertebrates that drift with water currents.

AMPHIPOD

A type of zooplankton with hard shells that have both swimming and walking feet.

To measure competition for food between jellies and fish, we looked at stomach fullness in threadfin shad, a fish that also eats zooplankton. If there was high competition for zooplankton between jellies and threadfin shad, the fish stomachs would be less full when the jellies were around. However, we found that the presence of Black Sea jellyfish made no difference in the fullness of threadfin shad; fish could eat just as much as they did when the jellies were not present. Were the shad switching what they ate to get full? Nope! Threadfin shad and jellyfish stomachs were found to contain mostly the same thing—amphipods [1].

This tells us that, at least right now, competition does not appear to be a problem. However, the study *did* confirm that there is overlap in food resources, which means that zooplankton-eating fishes would have to compete with jellies if their common food source (amphipods) ever became in short supply [4]. This is of some concern to scientists in the San Francisco Estuary because zooplankton-eating fish have already been declining for decades, and more competition for food could make that decline even worse.

IS THE FUTURE FULL OF JELLY?

It is difficult to predict the future of Black Sea jellyfish in Suisun Marsh. However, scientists think that climate change will cause summers to start earlier, be warmer, and last longer. If this happens, the Black Sea jellyfish could bloom sooner and stay longer. If jellies bloom earlier, fish that are born in the spring will still be small and vulnerable when the jellyfish bloom. Also, blooms could become even bigger. If the jelly population keeps rising, there may be more pressure on food resources for all the animals that eat zooplankton. So, it is possible that climate change could improve conditions for jellyfish, which could spell trouble for Estuary fish.

While it is difficult to predict the future, by looking at the past we can see that Suisun Marsh is certainly getting fuller with jellies. The Black Sea jellyfish population in Suisun Marsh has been increasing since the 1980s and in 2019, we saw the highest number of jellyfish *ever*: 21,478 jellies (Figure 2). So, how do we manage this species to prevent it from affecting fishes that we care about? One solution might be to change water conditions. Since the jellyfish prefer salty water, their numbers might be controlled by increasing the amount of fresh water flowing through the rivers that feed into the Marsh. A new experiment is being planned, which will allow more fresh water to flow through Suisun Marsh. Scientists hope that lowering the saltiness will benefit native fishes, while reducing the number of jellyfish by killing polyps with freshwater.

Black Sea jellyfish are here to stay, but their impacts can be reduced with good science and management. Scientists must continue to conduct experiments and monitor population trends. By studying the jellyfish, we can tell how changing conditions affect them and then pursue strategies to protect the Suisun Marsh ecosystem, by controlling the population of potentially deadly Black Sea jellyfish.

ORIGINAL SOURCE ARTICLE

Wintzer, A., Meek, M., and Moyle, P. 2011. Trophic ecology of two non-native hydrozoan medusae in the upper San Francisco estuary. *Mar Freshw Res.* 62:952–61. doi: 10.1071/MF10221

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EUROPEAN SCHOOL OF VARESE, AGES: 10–12

P5Ea are Earth-friendly eco-warriors. We are committed to looking out for each other and our planet, always willing to share our skills and resources. We are fabulously opinionated with "go for it" growth mindsets. We also love to be loud and we play a great game of cricket.

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John R. Durand studies the ecology of food webs and fish in estuarine environments as a senior researcher at U.C. Davis' Center for Watershed Sciences. He currently has several funded studies in the California Estuary, with projects including the ecological function of restored and managed wetland habitats, fish community composition across marginal habitats, and the effects of drought on the Delta.

MARIAH H. MEEK

Mariah H. Meek is an assistant professor at Michigan State University, where her lab uses genetic studies to better understand how to conserve and manage aquatic species. She got her Ph.D. at U.C. Davis where she spent much of her time on Suisun Marsh, catching jellies, and counting fish.

PETER B. MOYLE

Peter B. Moyle is Distinguished Professor Emeritus at U.C. Davis. He is a fish biologist and started the long-term research program on Suisun Marsh fishes and invertebrates in 1979.

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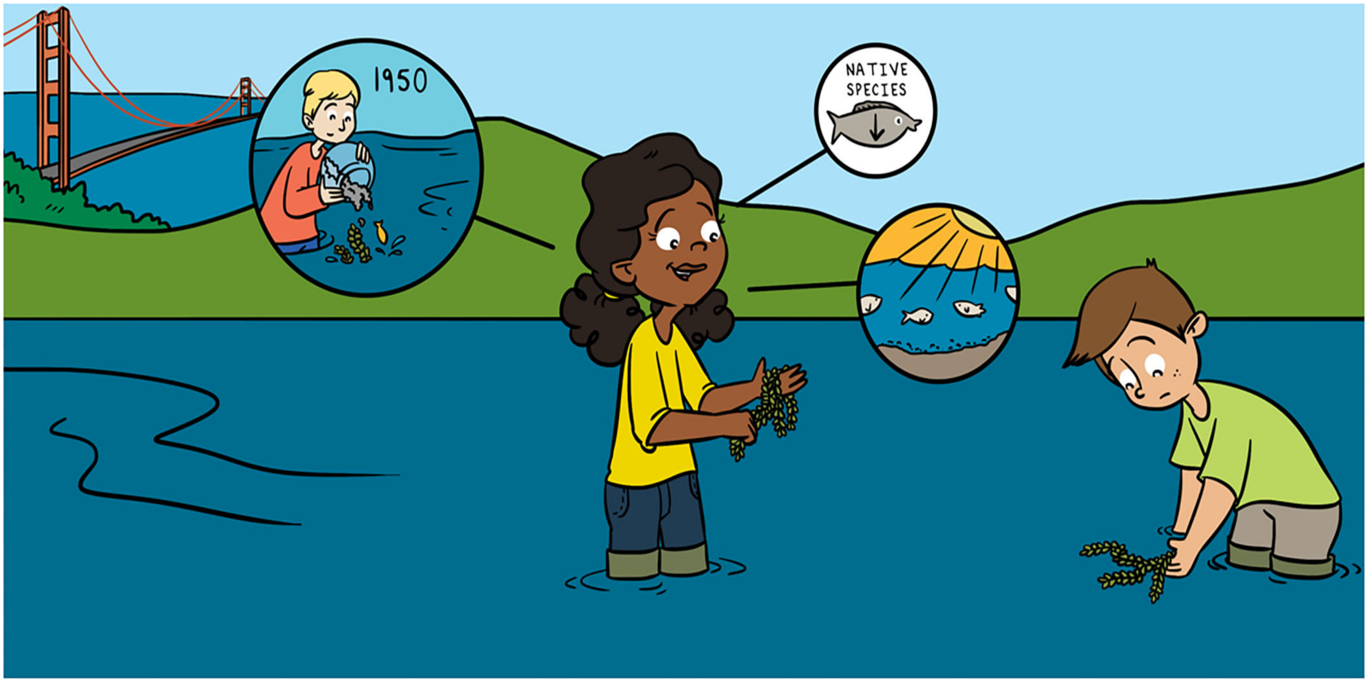

CAN PLANTS BE ENGINEERS?

J. Louise Conrad *

Delta Science Program, Delta Stewardship Council, Sacramento, CA, United States

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AGES: 10–11

When we think of engineers, we think of making a machine, like a car. Are there engineers for ecosystems? When an organism can make big changes to its environment, we call it an ecosystem engineer. In aquatic ecosystems like the San Francisco Estuary, underwater plants can be important ecosystem engineers because they can change water flow and water clarity. In the Estuary, a plant called Brazilian waterweed, which was introduced by humans, is one of the most important ecosystem engineers. With its leaves and stems, this plant traps tiny particles floating in the water, making the water clearer. Clearer water has made it easier for more plants to grow and these changes helped some non-native fish species to increase in number, while some native species declined. Introduction of Brazilian waterweed has led to an entirely different ecosystem, which has also affected how people use and take care of the Estuary.

WHAT ARE ECOSYSTEM ENGINEERS?

What do you think an engineer does? Human engineers make things, like machines or buildings. So, what would it mean for an animal or a plant to be an **ecosystem engineer**? Scientists that study animal and plant communities use this term to describe living organisms that make big changes in their own environments [1].

Beavers are a great example of ecosystem engineers. Beavers have sharp teeth that they use to cut down entire trees! They pile the cut wood on streams and rivers, making a dam. Once they finish, the water level above the dams rises, creating a pond. The edges of the pond also flood, creating a new habitat called a **wetland**. These new ponds and wetlands attract new species of fish, insects, and even birds. Is that not incredible? There are many other examples of ecosystem engineers, like termites and ants that build mounds and tunnels in the soil. While engineering these mounds and tunnels, they change how water drains through the soil and even the types of plants that can grow in that area [1].

WHAT ARE *INVASIVE* ECOSYSTEM ENGINEERS?

You now know that ecosystem engineers can be very powerful. Now, let us think about what happens when an ecosystem-engineering species comes to a place where it has never been before. In general, **introduced species** are brought by humans, either on purpose or by accident, to an ecosystem that is different from where they originally evolved. When the introduced species is also an ecosystem engineer, it can change how the ecosystem works, and even which other species will live there.

Many species are introduced to a new ecosystem, but never thrive in it. Some, however, can become quite at home and spread throughout the ecosystem, competing for food and space with the **native species** that already live there. When this happens, these introduced species are called **invasive species**.

When invasive species are also ecosystem engineers, they can change the basic parts of an ecosystem *and* cause harm to native species. Crayfish are a good example. Crayfish are ecosystem engineers because they burrow in the **sediment** to find food. When they invade rivers and lakes that have underwater plants, their digging destroys plant roots, and the plants die. When those plants die, other tiny plant species that float in the water, called **phytoplankton**, start thriving because the larger plants are no longer in the way. Through their extensive burrowing, crayfish can be invasive ecosystem engineers because they cause underwater plants to disappear and allow the phytoplankton to increase. Imagine how these changes might affect animals that were used to feeding on or living on the underwater plants. They might not be able to live in their home lake or river anymore. In general, once an invasive ecosystem engineer has made its home in a new place, it is likely that the ecosystem will never be the same again.

ECOSYSTEM ENGINEER

Any organism that changes its environment through its actions (such as beavers cutting down trees) or its physical structure (such as underwater plants trapping tiny particles in the water).

WETLAND

Land that is saturated with water. Marshes and bogs are all types of wetlands.

INTRODUCED SPECIES

Species brought to an ecosystem by humans, either on purpose or by accident. In aquatic ecosystems, humans can accidentally bring new species on the outside of their boats.

NATIVE SPECIES

Species that are living in a region where they originally evolved. Another term with the same meaning is "indigenous species."

INVASIVE SPECIES

Species that are introduced to a new to an ecosystem and cause harm to it, such as outcompeting and displacing the species that were already living there.

SEDIMENT

Solid material that settles to the bottom of a lake, river, or any waterway. Sediment can consist of particles of rock, minerals, and the remains of plants or animals.

PHYTOPLANKTON

Tiny, microscopic organisms living in the water that get their energy from the sun, just like plants.

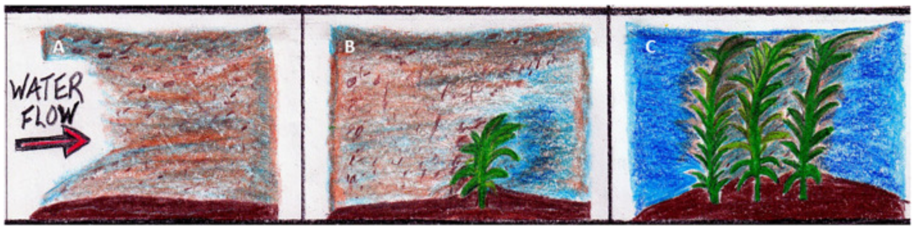

Figure 1

Figure 1

Ecosystem engineering by aquatic plants. **(A)** The water initially has many suspended particles, making it murky and cloudy. **(B)** When the first aquatic plants begin to grow, they capture some of the suspended particles, and cause other particles to fall to the bottom as sediment, creating a small patch of clear water. **(C)** As the plants continue to clarify the water, more plants grow because sunlight can penetrate deeper into the water.

ESTUARY

The body of water where a river connects with the ocean and the waters are affected by the rise and fall the ocean tides.

PLANTS CAN ALSO BE ENGINEERS

In rivers and **estuaries**, underwater plants (called aquatic plants) are some of the best-studied invasive ecosystem engineers. The leaves and stems of aquatic plants slow the movement of water and trap tiny floating particles of silt or clay. When these particles encounter a patch of aquatic plants, some will get stuck on the plants or fall to the bottom, becoming part of the sediment. This trapping of particles makes the water clearer. The clearer the water is, the more sunlight that can penetrate. More sunlight is good for the plants because they need it to grow.

When a new aquatic plant arrives in an ecosystem, it will trap just some of these floating particles. The water will clear up in a small area around the plant. Slowly, as the water clears, the plant will get more sunlight, grow more, and a small patch of the plant will begin to spread out to cover a larger area, even a whole river from one side to the other in some cases! The more plants there are, the more sediment will build up on the bottom, eventually reducing the water depth (Figure 1). Brazilian waterweed (Figure 2) is one invasive ecosystem engineer that creates sediment, clears up the water, and reduces water depth. Let us look at what happens when this plant comes to a new ecosystem.

INVASIVE AQUATIC PLANT ECOSYSTEM ENGINEERS OF THE SAN FRANCISCO ESTUARY

In the San Francisco Estuary, Brazilian waterweed was introduced before 1950, probably because people threw away the fish and plants from their aquariums right into the Estuary waters (which is illegal to do now). Today, Brazilian waterweed has spread throughout the Estuary, and even though other aquatic plant species have been introduced, it is still the most dominant one. Some areas that had few plants 30 years ago are now nearly entirely covered with invasive plants. The invasion of Brazilian waterweed and other aquatic plants into the San Francisco Estuary has made the water clearer than it used to be. Scientists estimate that, in some areas, more than two-thirds of the increased clarity may be due to the spread of invasive ecosystem engineering plants [2]! In beds of Brazilian waterweed, sediment can accumulate

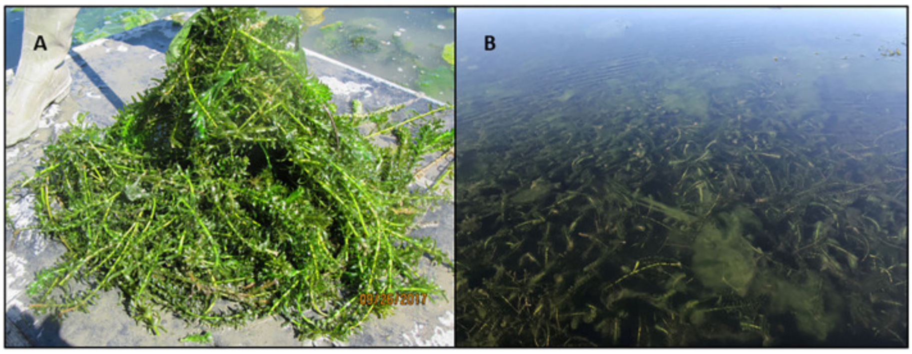

Figure 2

Figure 2

(A) Brazilian waterweed, after being pulled out of the water with a rake. **(B)** A thick bed of Brazilian waterweed in the San Francisco Estuary. (Photo credit: J. Louise Conrad).

twice as fast as it did before in shallow areas of the San Francisco Estuary [3].

Brazilian waterweed in the San Francisco Estuary has also changed the fish species that live in shallow areas. Previously, shallow areas had native fishes such as perch and minnows. Baby salmon also used shallow areas to feed, as they traveled through the Estuary to get to the ocean. Today, it is much more common to see introduced fish species such as largemouth bass and sunfish (Figure 3). What is the connection between Brazilian waterweed and the change in the most common species of fish?

Largemouth bass and sunfish were introduced into the San Francisco Estuary over a 100 years ago, long before Brazilian waterweed. For many years, these fish were not very common. However, once the invasive plants became widespread, the numbers of largemouth bass and sunfish increased [4]. These fish do well in clear water with lots of plants around them, and this is exactly the habitat that Brazilian waterweed creates. The clear water helps these fish to see and capture their prey. The plants offer hiding places to help small fish avoid deadly encounters with larger fish. Native fishes were accustomed to using murky water to hide from predators, but with the clear water created by the plants, native fish have nowhere to hide. So, with more predators such as largemouth bass, their chances of being eaten are much higher than they used to be. Unfortunately, the number of native fish has declined dramatically in the San Francisco Estuary.

PLANT ENGINEERS ALSO CHANGED THE ESTUARY FOR PEOPLE

When the plant ecosystem engineers changed the type of fish living in the San Francisco Estuary, they also changed people's lives. For example, it has become popular to fish for largemouth bass in the Estuary. There are now competitions to catch the biggest largemouth bass, and the reward for the winners can be a lot of money! But

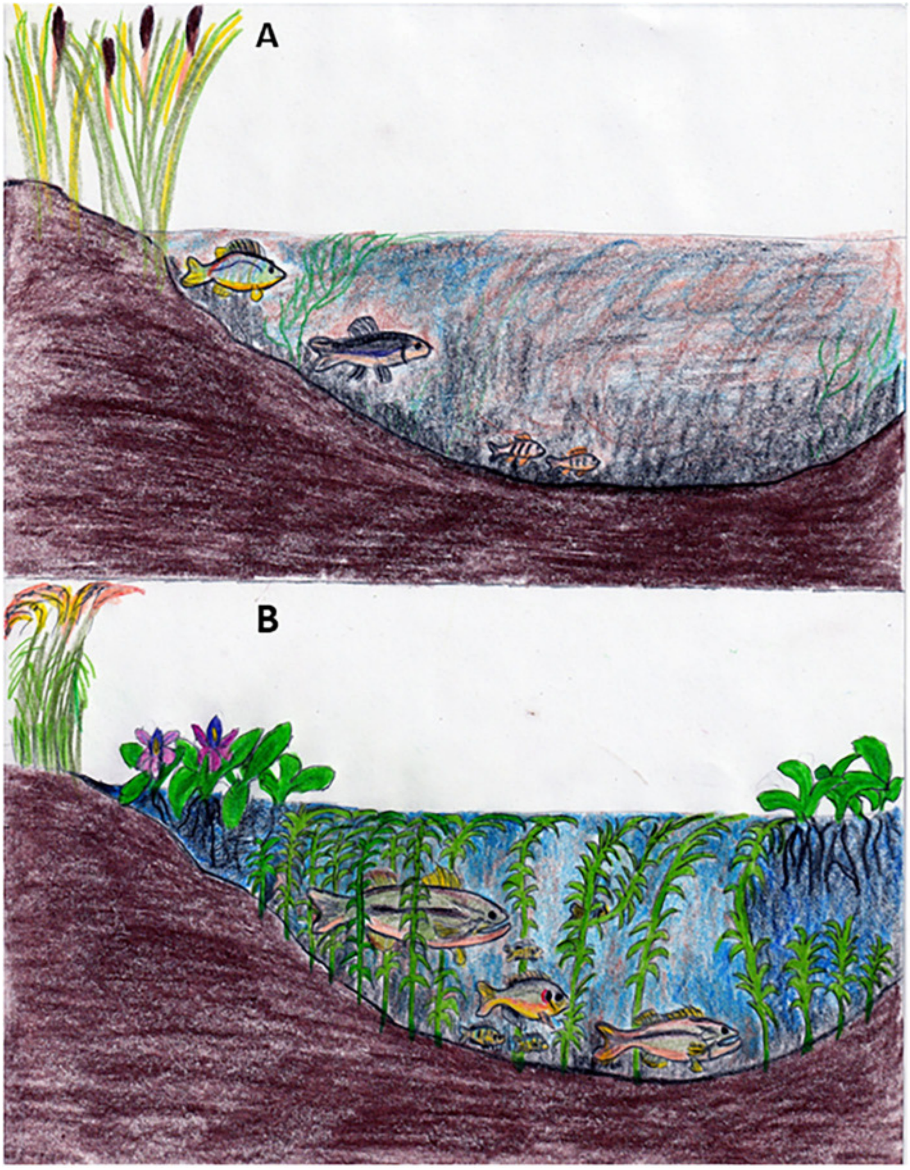

Figure 3

Figure 3

(A) Historically, the shallow-water areas of the San Francisco Estuary were probably cloudy, with relatively few submerged and floating plants, and were inhabited by native fishes such as tule perch, Sacramento blackfish, and migrating baby salmon. **(B)** Today, these shallow-water areas are filled with submerged aquatic plants that have clarified the water substantially, and there are floating plants at the water's edges. It is common to find non-native sunfish such as largemouth bass, redear sunfish, and bluegill sunfish.

Brazilian waterweed is so thick in some areas it has made it hard for boats to move through the waterways. The California government has worked to control the plant using chemicals that keep it from growing. However, the plants have become so widespread that they are difficult to control, and they will probably always exist in the San Francisco Estuary. Scientists are working hard to understand which chemicals are safe and work best, and if there are other ways of controlling the plants.

There are many opinions about whether the changes brought by invasive ecosystem-engineering plants are "good" or "bad." It all depends on what we value in the ecosystem: whether we value having historical habitats like wetlands and native fish species, or whether we value fishing for largemouth bass. It is up to the people living in and using the San Francisco Estuary, as well as the governments in charge of managing it, as to whether the invasive populations of plants and fishes should be diminished. Despite these differences in opinion, we can all agree that, when invasive plants are ecosystem engineers, they can have widespread effects on the rest of the ecosystem, from fish to people!

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YOUNG REVIEWERS

EUROPEAN SCHOOL OF VARESE, AGES: 10–11
Hey! We are in 5th class in a European School. Most of us are 11 years old and speak English. We all come from different countries that have different traditions. However, we always try to work as a team, and so far, we have successfully achieved

that. We are always trying to reach the best possible outcome and help each other. Our class has a wonderful teacher who has taught us a lot throughout the year. We are very happy and fortunate to take part in this project and hope for the best in the future.

AUTHOR

J. LOUISE CONRAD

When I was a child, my family spent many summers traveling across the United States. We enjoyed natural places along the way, and I loved to explore during our hikes. After that, I knew I wanted to study the environment and how people use it. When I was 20, I took a fish biology course from an inspiring professor, and I decided to keep studying fish. After completing my Ph.D., I led a study in the San Francisco Estuary about how fish interact with invasive plants, spending half my time on a boat! I am still fascinated with the shallow waters of the Estuary. *Louise.Conrad@deltacouncil.ca.gov.

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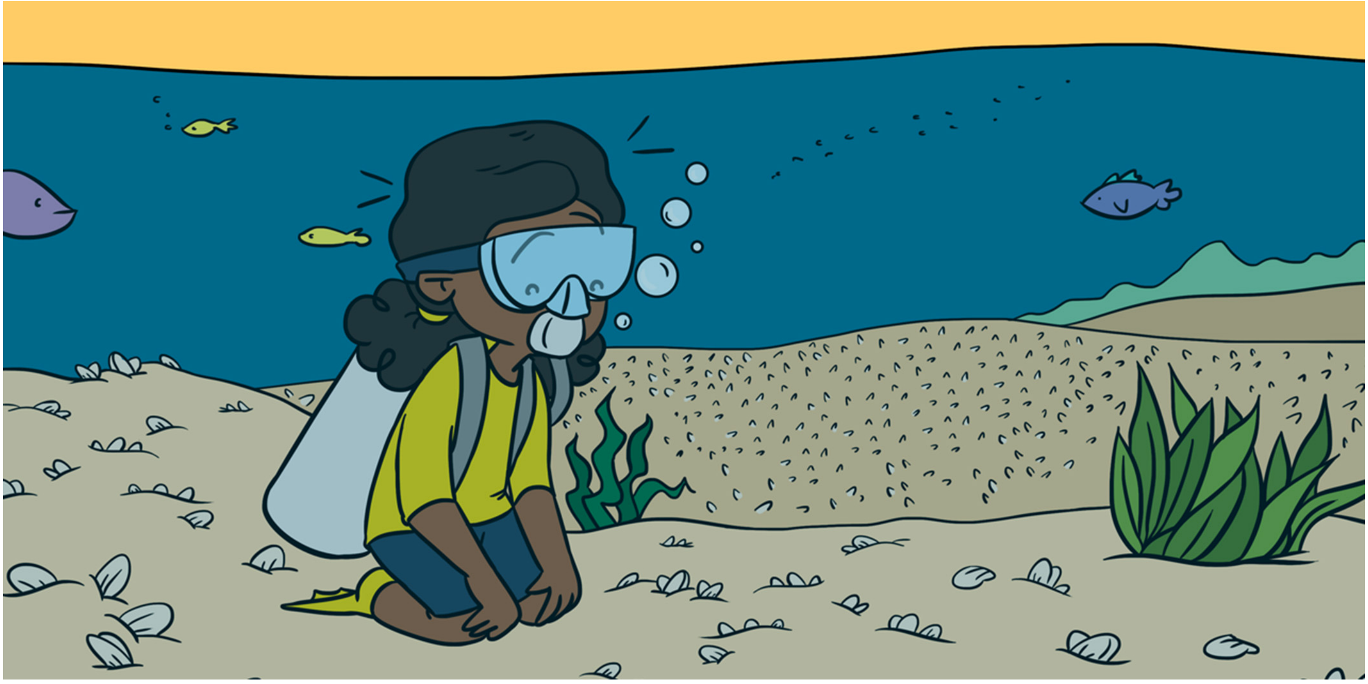

IF YOU GIVE A CLAM AN ESTUARY: THE STORY OF *POTAMOCORBULA*

Kelly H. Shrader, Emily L. Zierdt Smith, Francis Parchaso * ***and Janet K. Thompson***

U.S. Geological Survey, Benthic Laboratory, Menlo Park, CA, United States

YOUNG REVIEWERS:

ISABEL
AGE: 11

MARGARIDA
AGE: 13

MAYA
AGE: 10

When you look at San Francisco Bay, what animals do you see? You may see lots of fish, birds, harbor seals, and sea lions. What you do not see is a little clam (*Potamocorbula amurensis)* that changed the Bay. Many years ago, ships accidentally brought this clam into the Bay from Asia. Soon, they spread out all over in large numbers. Clams pump water through their gills and eat small particles of food that are in the water, like phytoplankton (microscopic aquatic plants) and other microscopic critters. *Potamocorbula* can pump water faster than other clams, and they can eat more than their share of phytoplankton. Sometimes, *Potamocorbula* eats phytoplankton faster than phytoplankton can grow! What problems does that cause for other animals that also eat phytoplankton? Does *Potamocorbula*'s invasion only have negative impacts? In this article, we dive to the bottom of the Bay to find some answers.

ESTUARY

Habitats where fresh water from rivers mixes with salty water from the ocean. Estuaries contain both fresh and salty water places where many plants and animals can live and grow.

INVASIVE SPECIES

Species introduced to an area that survive, reproduce, and spread, causing problems in the new area.

BALLAST WATER

Water carried by boats for balance that can be emptied and refilled while moving or stationary. Animals can be moved and released in new habitats when in the expelled water.

SALINITY

The amount of salt in a body of water.

WHO IS POTAMO?

San Francisco Bay is an **estuary** that is home to many different species. If you look around the Bay, you may find fish, birds, harbor seals, and even sea lions. What you cannot see are the worms, crabs, and clams that live on the bottom of the Bay. *Potamocorbula amurensis*, as scientists call it, is a species of clam that can be found across the world. We nicknamed this clam Potamo. As an **invasive species**, Potamo came from somewhere else and changed their new home. In 1986, ships accidentally brought Potamo into the San Francisco Bay from Asia in their **ballast water** [1]. Soon after they arrived, Potamo liked their new home so much that they spread rapidly. Eventually, there were over 10,000 clams per square meter, which is the same as having 2,800 clams spread out on top of your school desk [1] (Figure 1)! But how could Potamo spread so much, and how did their invasion change San Francisco Bay?

POTAMO'S SPREAD AND SUCCESS IN SAN FRANCISCO BAY

There are four factors that allowed Potamo to spread out and be successful in the Bay. First, Potamo tolerate many different levels of salt in the water, known as **salinity**, and that allows them to survive when salinity changes in the bay [1, 2]. Second, Potamo survive in

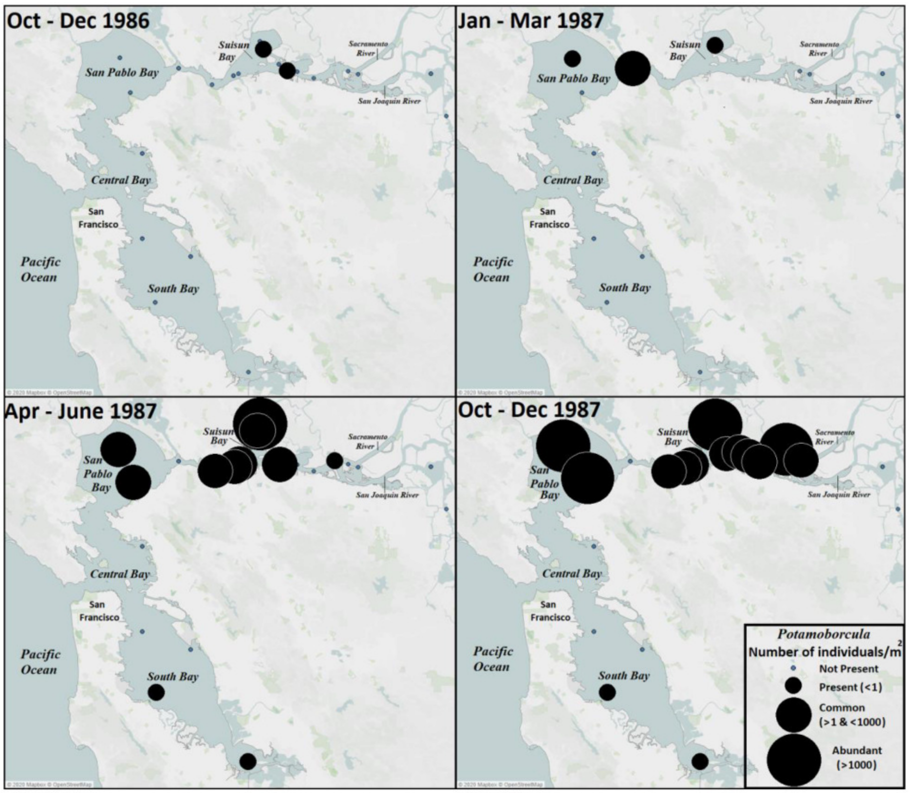

Figure 1

Figure 1

Initial spread and distribution of Potamo in San Francisco Bay, from 1986 to 1987. When it was introduced in 1986, there were only a few Potamo found in the area. Just 6 months later, there were clams all over the northern end of San Francisco Bay! One year after they were first introduced, there were thousands of Potamo in the Bay, and they are still there today.

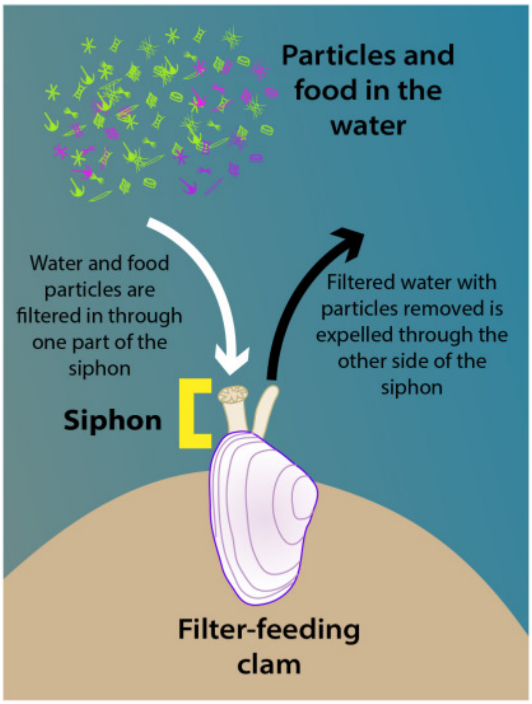

Figure 2

Figure 2

A clam brings water in through its siphon (white arrow) and filters the water through its gills to remove food particles such as phytoplankton that are suspended in the water. The clam then expels the water back out through the other part of its siphon (black arrow).

different types of **sediment**, or material that make up the bottom of the Bay, such as mud and sand. This makes Potamo even better at living in many parts of the bay because they can get comfortable no matter what sediment they live in [1, 2]. Third, the clams live in both deep and shallow parts of the Bay [1, 2]. Fourth, Potamo survive in the cold winter and the hot summer water temperatures [1]. Their ability to survive in all these different conditions allowed Potamo to spread out all over San Francisco Bay.

SEDIMENT

The material that settles to the bottom of a body of water, like mud, sand, and silt.

Like other clams, Potamo eat using a process called **filter-feeding**. Unlike humans, clams do not have heads, so they do not eat like we do. Instead, they have gills like fish and tubes called siphons that they use to eat and breathe. Clams can extend their siphons out of their shells like a straw to suck water. The gills act as a screen that traps the food particles that are in the water, allowing clams to filter and expel the water and keep the food. From the gills, the food particles move toward the mouth where they are eaten and digested [2] (Figure 2).

FILTER-FEEDING

A method of eating that separates suspended food particles from water by passing the water through a filtering structure, like gills. Some animals that filter-feed are clams, whales, and fish.

Potamo filter water very quickly, which means they can eat a lot of food in a short period of time [3]. For example, 300 clams in a square meter, or 30 clams in a square foot, can filter 3,785 liters of water in 1 day. That is enough water to fill over 23 bathtubs [4]! Potamo are also not picky eaters and can eat different organisms, such as **phytoplankton** and bacteria [1]. This means that they always have something to eat.

PHYTOPLANKTON

Tiny, drifting plants that live in the water and get energy from the sun and nutrients from the water. Phytoplankton are eaten by zooplankton, clams, fish, and whales.

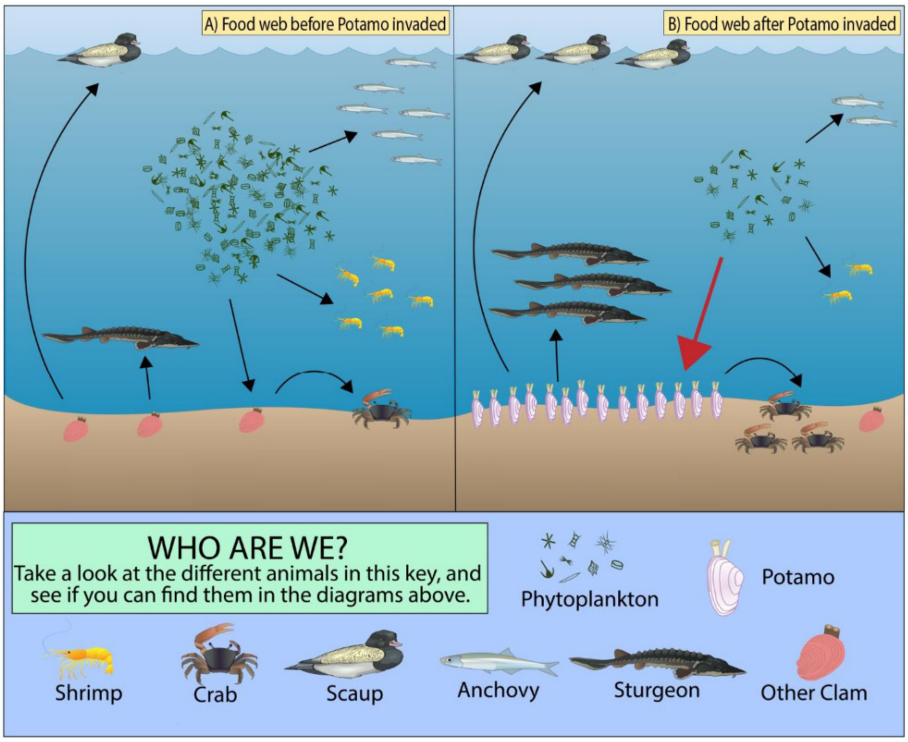

Figure 3

Figure 3

(A) Before Potamo arrived in San Francisco Bay, phytoplankton supported large fish populations. The black arrows show what eats what in the food web. **(B)** After the invasion of Potamo, less phytoplankton was available for other species to eat, which changed the food web. The red arrow indicates that Potamo eat more phytoplankton than the other species in the diagram (The images used in the figure are courtesy of Tracey Saxby, Dieter Tracey, Kim Kraeer, Lucy Van Essen-Fishman, and Jane Thomas from the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/), and Kamil Sulima from svg-clipart.com for the scaup).

Potamo occupy the same territory as other animals, and they have several different ways to compete with unwanted neighbors. They burrow near the sediment surface, sometimes leaving one-half to two-thirds of their shells above the sediment. By sticking out of the sediment, Potamo do not leave much surface space for other animals to settle. The clams can also live very close together, which makes it hard for other animals to find enough space to settle next to them. Potamo's large numbers, shallow burrowing, and efficient filter-feeding limit space and food for potential neighbors. When combined with Potamo's ability to tolerate many different environmental conditions, they can outcompete many other species [1].

PHYTOPLANKTON AND THE VERY HUNGRY CLAM

One of things that Potamo like to eat is phytoplankton. Phytoplankton are an important part of the food web, and many other creatures rely on them. Before Potamo invaded the Bay, the amount of phytoplankton changed seasonally; their numbers were low during winter and spring and "bloomed" during summer and fall. After Potamo arrived and spread out, phytoplankton numbers remained low during summer and fall when they normally peaked [3]. Since Potamo's arrival, phytoplankton has consistently decreased. Potamo can eat phytoplankton faster than phytoplankton can grow, which can limit phytoplankton from blooming [4] (Figure 3).

Luckily, Potamo cannot wipe out *all* the phytoplankton, due to the depth and flow of the water. In shallow water, Potamo pump all the water above them and quickly eat the available phytoplankton. However, in deep water, Potamo can only filter the water near the bottom, so the phytoplankton near the surface are safe. The flow of water can also move phytoplankton away from the clams before Potamo have time to filter the water, so the phytoplankton can escape being eaten [3].

Freshwater from rivers and rain mix with salty ocean water to change the estuary's salinity, and animals respond to these changes. Phytoplankton move with the water, so they are exposed to changes in salinity as tides push the water back and forth between the ocean and Bay. Clam populations also move with salinity, but in a different way over a much longer time. Baby clams float in the water and settle in new places as they are pushed around by the tides, much like seeds floating in a gentle breeze. However, like trees that put down roots, individual clams cannot leave once they settle on the bottom. Therefore, Potamo cannot chase phytoplankton, but must wait for phytoplankton to come to them [4].

Phytoplankton are at the base of the food web, which means they are a food source for animals like clams and fish. The clams and fish are then eaten by other animals, like larger fish and crabs, which can then be eaten by bigger animals, like ducks, sharks, and sea lions. When there are not enough phytoplankton, the entire food web is affected. **Zooplankton** are small organisms that live in the water that can eat phytoplankton. Since Potamo moved in and started eating so much phytoplankton, the number of zooplankton has decreased, and zooplankton predators (like shrimp and anchovies) have less to eat and have also decreased since Potamo have invaded the Bay [4] (Figure 3).

ZOOPLANKTON

Tiny aquatic animals that eat bacteria, phytoplankton, and other zooplankton. They are eaten by clams, shrimp, krill, and fish.

IS POTAMO BAD NEWS FOR EVERYONE?

Potamo's invasion is not only negative! The large numbers of Potamo have made more food available for bottom feeders such as diving ducks, sturgeon, and crabs [1, 4]. One of the species that benefits from Potamo is the lesser scaup, a bottom-feeding migratory bird that spends winters in the Bay [5]. Before Potamo, the lesser scaup fed on a native clam, called *Macoma balthica* (nicknamed Macoma).

Let us take look at the details of clams as prey. The amount of energy scaups get from clams depends on many factors: how nutritious the clam is, how easily it is digested, how deep the clam is buried, and how many clams a scaup eats during one dive. The best food source gives scaups the most energy—more energy than they use to catch, digest, and crush the clams [5]. Potamo have higher nitrogen and fat content, and three times the energy available than Macoma. Potamo's shells are thicker and harder to crush than Macoma's, yet Potamo are the better food source. Scaups spend more energy digesting Potamo's shells, but they get more energy back from eating Potamo than Macoma [5].

Potamo are more available than Macoma, and scaups can capture more clams during a single dive by eating Potamo. Diving takes a lot of energy for a bird—they must hold their breath and push against the water pressure to get to the bottom. Therefore, they want to capture as many clams as possible per dive. Scaups eat clams buried <5 centimeters (about 2 inches) deep. Most Potamo live within this range, while only half of Macoma live at these same shallow depths [5]. So, overall, Potamo are a better food source for the lesser scaup than Macoma are.

POTAMO: MAYBE GOOD, MAYBE BAD, AND DEFINITELY HERE TO STAY

While San Francisco Bay is not Potamo's original home, they show no signs of leaving. Humans do not eat these clams, so we must depend on their predators to control the clam populations. As we have explained, Potamo have both helped and harmed its new home. Food webs can be messy, and relationships between species can become complicated as new species are introduced, as with Potamo. While the future of San Francisco Bay species and Potamo's dominant status in the Bay remain unknown, one thing is certain: nature is always changing and evolving.

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YOUNG REVIEWERS

ISABEL, AGE: 11

Hello, I am Isabel. I am 11 years old and I really like writing stories. I also like reading. I am really interested in diplomacy.

MARGARIDA, AGE: 13

My name is Margarida, I am 13 years old and I like reading, climbing, and writing. I love science, especially anything about black holes and I have absolutely no idea what I want to do when I grow up. I also really like biology.

MAYA, AGE: 10

Maya loves to draw and learn about animals. Her favorite subject is reading and she just read a book about cats! She likes to look for insects outside. This summer she went swimming in the Lake Michigan in Chicago.

AUTHORS

KELLY H. SHRADER

I am a biologist with the U.S. Geological Survey (USGS), Water Mission Area. My interest in ecology started when I was in elementary school, watching the animals in my own backyard interact with one another and their environment. My desire to pursue research began at U.C. Santa Cruz, where I received a degree in ecology and evolutionary biology. I am interested in spatial ecology, or where animals are found in the environment and why. My work in the Benthic Laboratory investigates where two species of invasive clams live in San Francisco Bay and what impact they have on other animals.

EMILY L. ZIERDT SMITH
I am a biologist with the U.S. Geological Survey Benthic Laboratory. Ever since I was little, I have been interested in being outside, always running from tree to tree, to rocks, and to nearby streams. I took my passion for being outdoors to U.C. Santa Cruz, where I received a degree in environmental studies and a degree in ecology and evolutionary biology. I am interested in the restoration and conservation of different ecosystems. Our laboratory studies how the community of animals that live on the bottom of the San Francisco Bay changes and the long-term impacts of those changes.

FRANCIS PARCHASO
I am a biologist at the U.S. Geological Survey. I have a master's degree in marine biology. I work with a team of scientists that studies San Francisco Bay. I study benthic animals, that is, the animals that live in the bottom of San Francisco Bay. My research includes clam feeding behavior, reproduction, and physiology, as well as the effects of clams on the food web and ecosystem. Our work involves a lot of time on a boat collecting samples and time in the laboratory identifying and counting all the animals that we find in the samples. *parchaso@usgs.gov

JANET K. THOMPSON
I have been a biologist at the U.S. Geological Survey for 40+ years. I have a master's degree in marine biology and a Ph.D. in civil engineering. My work is focused on understanding how animals that live on the bottom affect the structure of the aquatic ecosystem and how changes in which species live on the bottom can result in long-term changes to the food web. Having spent most of those 40+ years going into the field, I now spend much of my time analyzing the data and writing.

frontiers FOR YOUNG MINDS

EARTH AND ITS RESOURCES
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HOW CAN WE USE COMPUTER MODELS TO LEARN ABOUT THE SAN FRANCISCO ESTUARY?

***Michael L. MacWilliams*[1*]*, Eli S. Ateljevich*[2] *and Stephen G. Monismith*[3]**

[1] *Anchor QEA, LLC, San Francisco, CA, United States*

[2] *California Department of Water Resources, Sacramento, CA, United States*

[3] *Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, United States*

YOUNG REVIEWER:

ANNA GIULIA

AGE: 13

Computer models are an important tool that we can use to learn about the San Francisco Estuary. The San Francisco Estuary is a complex environment where salty water from the Pacific Ocean mixes with freshwater from rivers, because of tides, wind, and waves. These physical processes can be described using mathematical equations, which can be solved using computers. Using these equations to represent conditions in the San Francisco Estuary and solving them is called hydrodynamic modeling. Modeling of conditions in the Estuary requires an understanding of physics, mathematics, and computer science, which are combined to help us learn about the processes and environments in the Estuary. Models can be used to predict flooding and to design levees. They can also be used to help us improve how we manage the Estuary to provide a reliable water supply and to protect habitats for plants and animals.

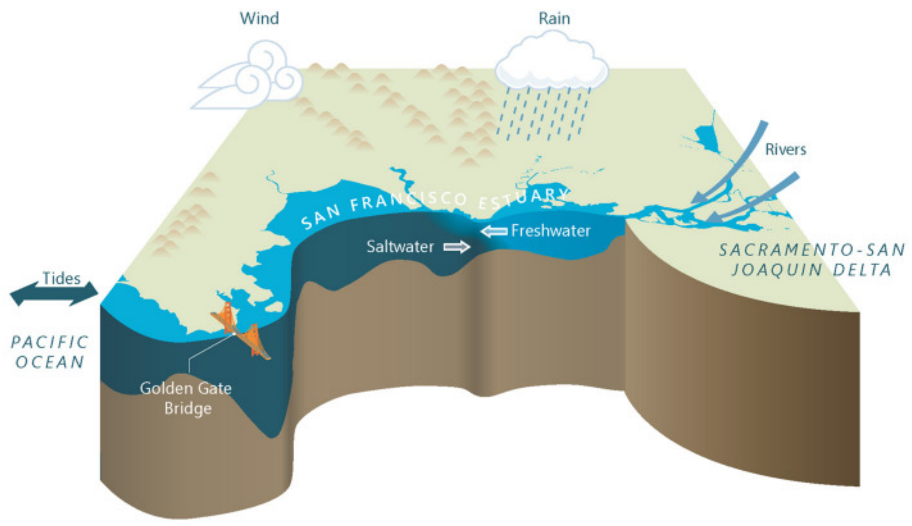

Figure 1

Figure 1

Profile of the San Francisco Estuary from the Pacific Ocean to the Sacramento-San Joaquin Delta. Denser saltwater from the Pacific Ocean moves in and out of the Estuary with the tides and flows landward, under the fresher surface water from rivers and rainfall. The freshwater and saltwater are mixed in the Estuary because of tides, wind, and waves.

INTRODUCTION

Every day, tides move saltwater from the Pacific Ocean in and out of the San Francisco Estuary (California, USA) through the Golden Gate. **Estuaries** are complex environments where saltwater from the ocean mixes with freshwater from rivers because of tides, wind, and waves (Figure 1) [1]. Two large rivers and several smaller ones join to form the Sacramento-San Joaquin Delta (the Delta) at the upstream end of the San Francisco Estuary (the Estuary). Many smaller streams and rivers flow directly into the Estuary. The Estuary provides nearby farms with the water needed to grow crops and it also serves as a source of drinking water for millions of people. In addition, the Estuary provides important habitats for many species of birds, fish, and other animals.

ESTUARY

A partly enclosed body of water where freshwater from rivers mixes with saltwater from the ocean.

One way to study the complicated environment of the Estuary is to use **computer models**. Building computer models of natural ecosystems like the Estuary requires an understanding of physics, mathematics, and computer science [2]. Equations can be used to describe the physical processes that control the flow of fluids, such as air or water. These equations can be solved using computers, to predict things like how air flows around the wings of an airplane, or how water moves in and out of the Estuary because of tides. By solving these equations, we can evaluate whether an airplane will fly, or how water flow, **salinity**, and habitats in the Estuary may change in the future. We can use computer models of the Estuary to understand the effects of building a new harbor or restoring a wetland. We can also use these models to plan for future changes to the Estuary that result from climate change or sea-level rise.

COMPUTER MODEL

A program that runs on a computer to solve a set of mathematical equations.

SALINITY

The amount of salt dissolved in a body of water. Salinity is measured in Practical Salinity Units (PSU), which is a measurement based on conductivity.

RECIPE FOR AN ESTUARY

The most easily observable feature of the San Francisco Estuary is the twice-daily rise and fall of the water levels by as much as 2 meters because of the tides. Tides in the Estuary are caused by the earth's rotation and the gravitational pull of the moon and sun on the Pacific Ocean. When the water level in the ocean rises, water floods into the Estuary through the Golden Gate. When the water level falls, water ebbs back out into the ocean. These ebb and flood currents can be quite strong, up to 2 meters per second under the Golden Gate Bridge. Each day, as much as 3.5 billion cubic meters of water move in and out of the Estuary due to tides. That is enough water to fill 1.4 million Olympic-size swimming pools. Tidal currents mix whatever is in the water and they also erode sediments on the bottom of the Estuary.

Strong winds also blow over the surface of the Estuary. These winds drive currents and generate surface waves. Wind-driven currents and waves are much stronger and more important in the large, shallow areas of the Estuary. Like tidal currents, wind-generated waves also are important for sediment erosion.

While tides and surface waves are clearly visible, an equally important feature is one that is not so easily seen. Because freshwater from rivers is lighter (less dense) than saltwater, fresh river water tends to float on top of the salty ocean water as it makes its way seaward, out to the ocean. As the water moves back and forth with the tides, the denser ocean water flows landward, under the fresher surface water. The circulation of water caused by the seaward currents at the water surface and the landward currents near the bottom is called **gravitational circulation**. The density-driven currents that cause gravitational circulation are generally weaker than tidal currents. Over time, however, gravitational circulation moves salt upstream into the Delta, the freshwater part of the Estuary. This is known as **salinity intrusion**. If the water in the Delta becomes too salty, it can no longer be used for drinking or watering crops. As a result, one of the most important uses of computer models of the Estuary is to predict how far salt will intrude into the freshwater reaches of the Estuary.

GRAVITATIONAL CIRCULATION

The residual flow pattern in an estuary caused by the density difference between seawater near the bed and fresher river water near the surface which results in salinity intrusion.

SALINITY INTRUSION

The upstream movement of saltwater beneath freshwater due to gravitational circulation.

COMPUTER MODELING

Before computers were as fast as they are today, physical models were built to understand how water flows in the Estuary. These physical models look like swimming pools but are shaped like small versions of the Estuary. They have pumps to make tides and are filled with salty water on the "ocean" side. The United States Army Corps of Engineers still operates a physical model of the Estuary for educational purposes. Today, using modern computers, it is possible to simulate flows in the Estuary more easily and accurately than with a physical model.

Computers can solve the complicated mathematical equations that show how water responds to tides, river flows, and wind [3]. Solving these equations that show how water moves in an estuary is called **hydrodynamic** modeling.

HYDRODYNAMICS

The study of the motion of fluids.

CONSERVATION OF MASS

The principle of conservation of mass states that in a closed system the amount of mass remains constant over time.

One example of a law of physics that must be included in a computer model of any natural system is the principle of **conservation of mass**. In the Estuary, this principle tells us that water can move around from area to area, but it is not created or destroyed. If there is a difference between the water flow into a region and the water flow out of that region, it means that the amount of water stored in that region has changed. The same thing is true for salt moving in and out of the area.

To figure out what is happening in the Estuary, models need a lot of information about the physical forces that affect the Estuary. The forces that act on the Estuary include tides, river flows, and wind (Figure 1). These forces must be accurately measured, and those data must be entered into the model so that the model can accurately predict conditions in the Estuary. For this reason, computer modelers work with scientists, data collectors, and even other modelers to get the information models need.

Since the Estuary is so large, to create an accurate computer model of the water flow, the area of the Estuary (Figure 2A) must be divided up into individual small areas called cells (Figure 2B). The computer repeatedly calculates movement of water between each of the cells over time. One of the hardest aspects of the calculation is that the flows into and out of *all* the cells must agree. This means that millions of equations must be solved together, using what mathematicians call simultaneous equations. As fast as computers are today, they still struggle with problems of this size.

Creating a model of the Estuary is a big undertaking. Once the initial work is complete, models can be used to simulate many different things, such as currents, waves, salinity, temperature, and the movement of organisms, nutrients, and sediment (Figure 2C).

COMPUTER MODELS HELP US UNDERSTAND THE PAST, PRESENT AND FUTURE OF THE ESTUARY

Computer models are powerful tools that help us to answer "what if" questions about the Estuary. We can develop computer models that include different changes to the Estuary and compare the results from these models to help understand how these changes affect the Estuary.

Computer models can be used to predict which areas of the Estuary are most likely to be flooded during storms or due to sea-level rise.

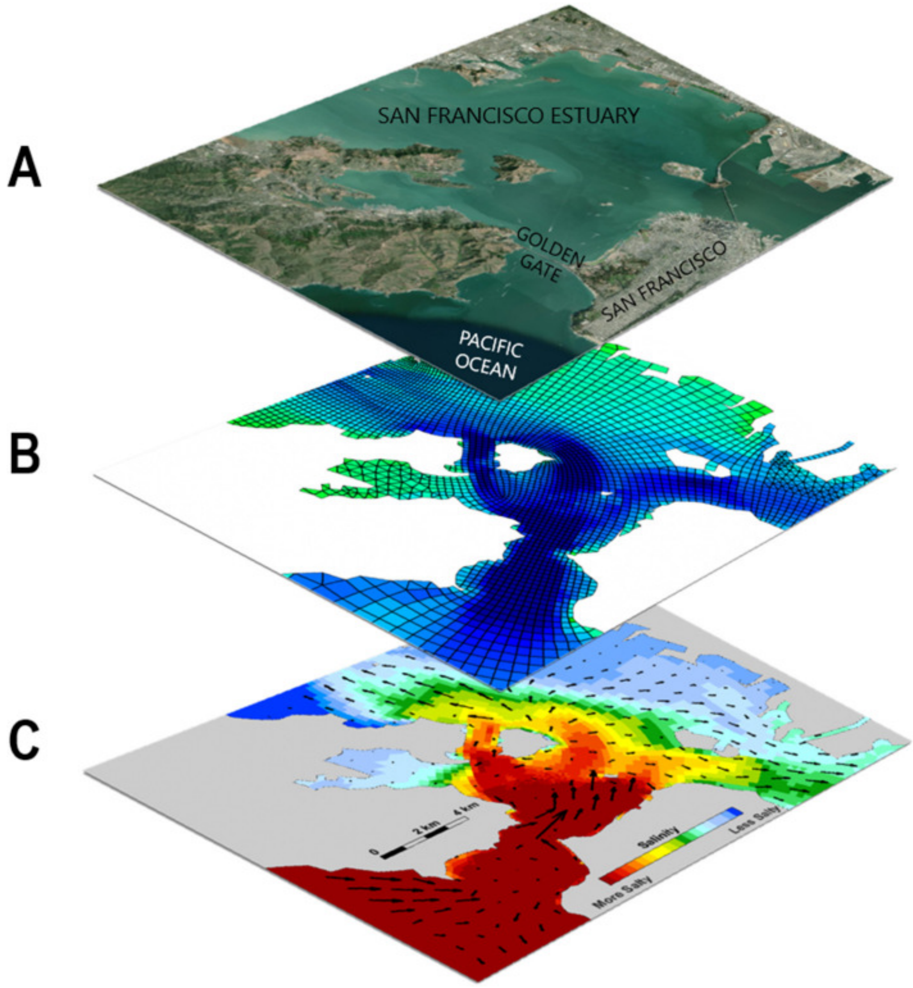

Figure 2

Figure 2

(A) Aerial view of the mouth of the San Francisco Estuary near the city of San Francisco. **(B)** To create a computer model, the area of the Estuary is divided up into many smaller grid cells. Calculations are performed simultaneously for all cells [4]. **(C)** Computer models can be used to predict different conditions in the Estuary. The black arrows show the predicted direction of water flow during flood tide that brings salty water (red) from the Pacific Ocean into the San Francisco Estuary through the Golden Gate where it mixes with the less salty water (blue).

We can use these results to estimate how high levees must be built to protect the homes and businesses that surround the Estuary. Many large technology companies in Silicon Valley have offices right next to the water. Computer models are being used to help us understand how high the levees must be to protect their buildings from future flooding and to restore the nearby wetlands. Recent modeling work by the United States Geological Survey was used to develop an online interactive mapping tool [5] that shows which areas are likely to be flooded because of storms and sea level rise (Figure 3A).

Habitats in the Estuary have changed over time because of human activities, such as draining marshes, building levees, and dredging channels. Computer models can be used to predict how habitats for fish and other organisms can be affected by these changes. One important habitat in the Estuary is called the **low salinity zone** (Figure 3B). The low salinity zone is an important transitional area between the salty water in the ocean and the fresh river water in the Delta. Computer models have been used to improve our

LOW SALINITY ZONE

The region of the estuary where salinity is between 0.5 and 6 practical salinity units. This region provides important habitat for many fish and other animals that live in estuaries.

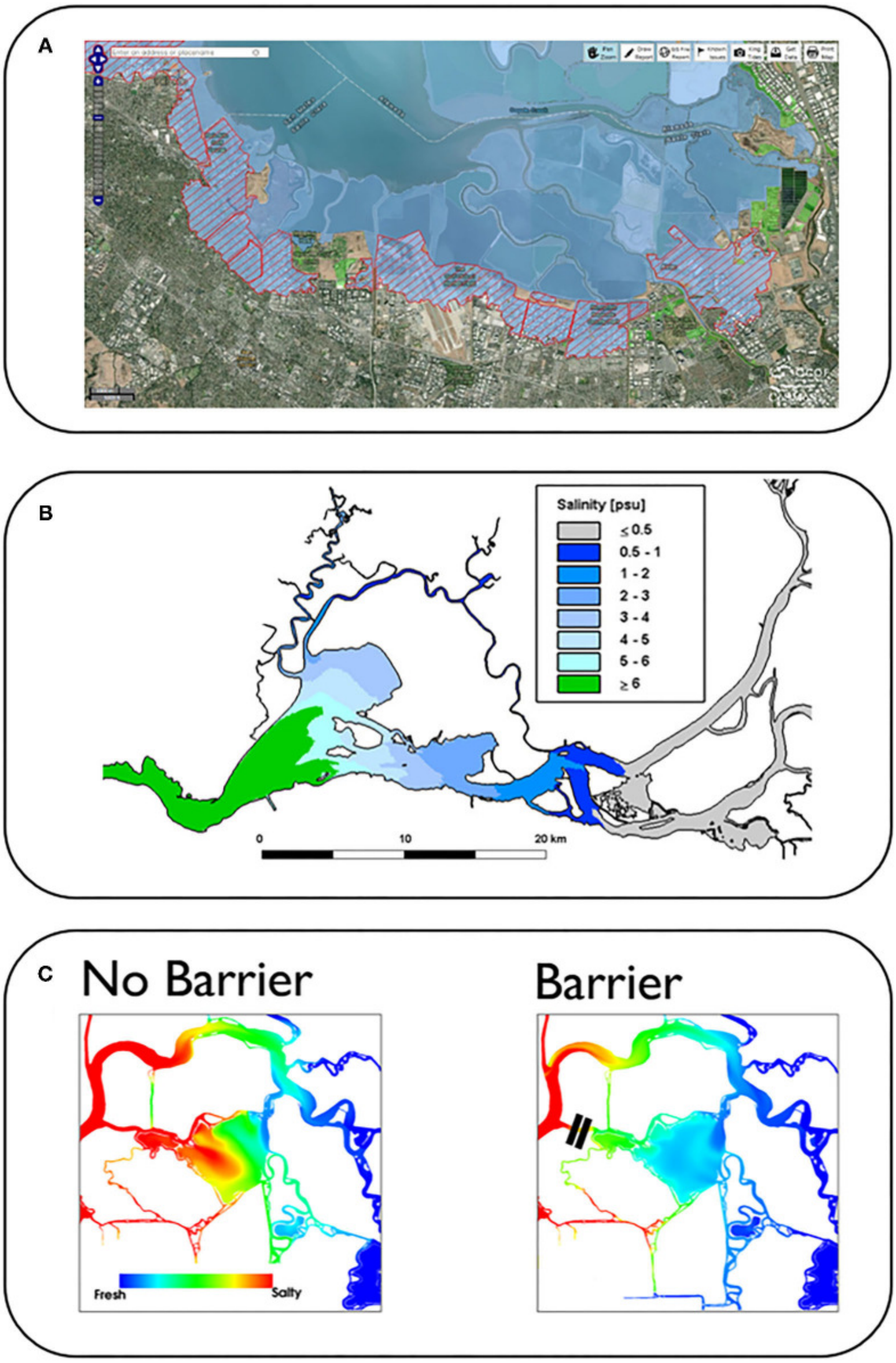

Figure 3

Figure 3

(A) Areas of Santa Clara County that are likely to be flooded (red outline) if sea level rises by 1.5 m [5]. **(B)** Predicted location of the low salinity zone in the Estuary (blue) during summer of a wet year. The low salinity zone provides important habitat for many fish [4]. **(C)** A computer model was used by the California Department of Water Resources to show that an emergency barrier (double black lines) could reduce the amount of salty water entering the Delta during a drought [2].

understanding of how the low salinity zone is affected by the amount of freshwater that flows in from the Delta [4].

During periods of drought, reduced flow from rivers can cause an increase in salinity intrusion. If too much salty water from the ocean moves into the Delta, the water becomes too salty to use for drinking water. The California Department of Water Resources used a computer model to test whether an emergency barrier could reduce the amount of salty water entering the Delta during a drought (Figure 3C) [2]. The model showed that the barrier reduced the amount of salty water that entered the Delta.

Computer models have increased our understanding of what the Estuary was like in the past and how humans have changed it. Computer models are much faster, more versatile, and more accurate than the physical models that were used in the past. Computer modelers take real-world problems and describe them in the language of mathematics and computers. They then interpret the large amount of data produced by computer models to make the results understandable and useful. The data produced by computer models will help us understand how future changes will affect the Estuary and the communities that depend on it, so that we can protect homes and businesses as well as the health of the Estuary.

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YOUNG REVIEWER

ANNA GIULIA, AGE: 13

I am Anna Giulia and I am 13 years old. I like school and my favorite subjects are History and Science. I love reading and my favorite book is Harry Potter and the Deathly Hallows. In my free time I enjoy playing flute, dancing and hanging out with my friends.

AUTHORS

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Michael is a licensed civil engineer and a computer modeler. Michael completed his undergraduate studies at the University of Notre Dame and his graduate degrees at Stanford University. Michael started a consulting company that specialized in building and applying computer models to rivers and estuaries. Michael has developed models of many estuaries including San Francisco Bay and Chesapeake Bay. Michael currently works at Anchor QEA, an environmental science and engineering consulting firm working to improve the environment and our communities. His work includes using computer models to help restore habitat and plan for sea level rise. *mmacwilliams@anchorqea.com

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Eli is a researcher and engineer working for the State of California. He grew up rafting in California and loves water. He also loves math and computers, most of all using them on problems people care about. His job is to study the Bay-Delta and help the state make decisions that balance human needs with protecting the environment. Eli recently used a computer model to decide how to restore a flooded part of the Delta into a wetland. He is most interested and concerned about climate change—he recently had to drive through a scary wildfire with his family!

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Stephen is a professor of civil and environmental engineering at Stanford University who specializes in the study of flows in the natural environment. He has been interested in issues involving San Francisco Bay since he was a graduate student at U.C. Berkeley. In addition to his work on estuaries, he has also studied flows in lakes in Asia, Europe, and the U.S. Much of his recent work has focused on kelp forests and coral reefs. A central theme in his work is the application of engineering approaches to the management of water bodies like the Bay.

frontiers FOR YOUNG MINDS

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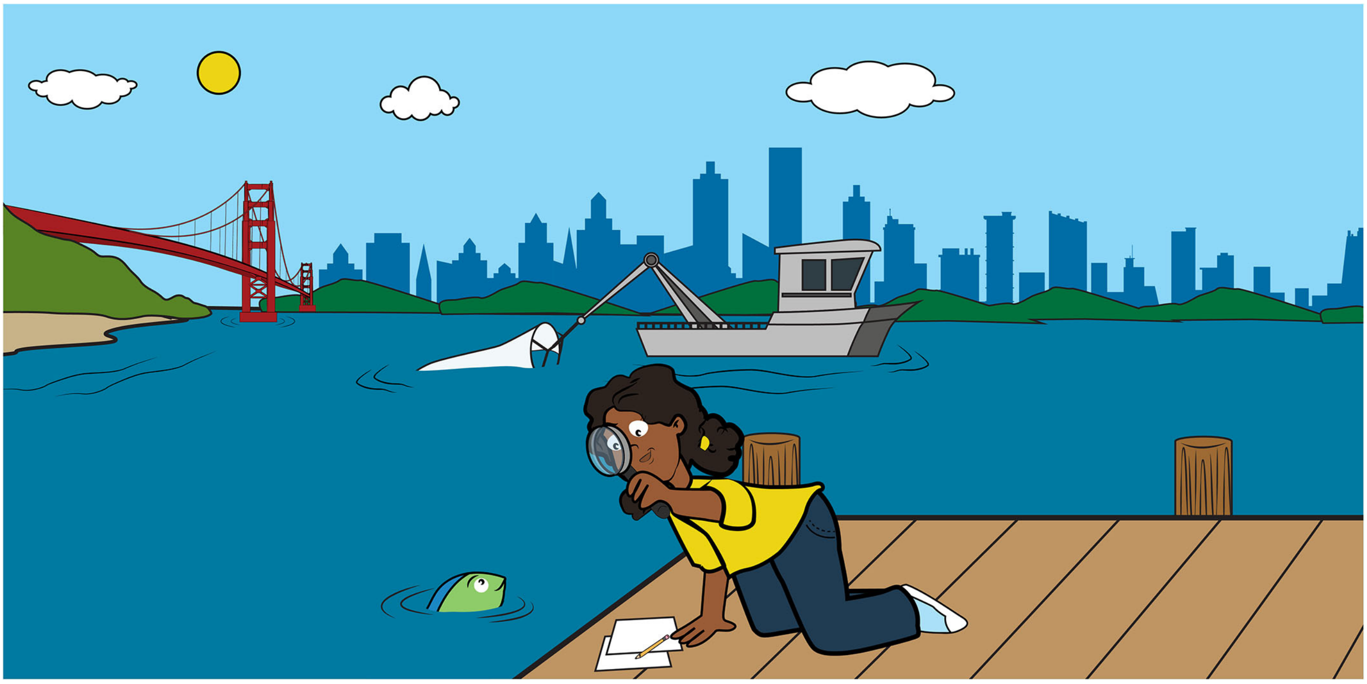

WHERE THE YOUNG FISH ARE: MONITORING FOR CONSERVATION

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YOUNG REVIEWERS

SCUOLA EUROPEA DI VARESE

AGES: 12–13

The San Fransisco Estuary is an important nursery for young fish. Scientists use special nets and techniques to identify and count small fish in the estuary. Knowing how many and where the young fish are helps managers avoid harm to fish populations. Water flowing in rivers naturally flows out to sea, but in the San Francisco Estuary, some of that water is stored in reservoirs or pumped to other parts of California, which can have a negative impact on fish populations. These and other challenges to fish have resulted in severe declines in numerous species. In this article we will describe how we monitor young fish population trends. We also describe how the sampling method changes depending on the habitat and time of year sampling occurs. Finally, we explain how the information is used by scientists, managers, and the public within the San Francisco Estuary, California, USA.

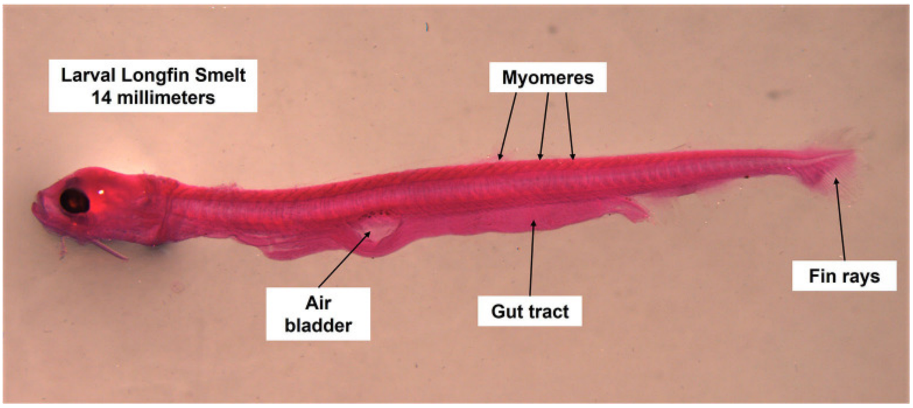

Figure 1

Figure 1

A larval longfin smelt that is 14 mm long. The key parts used in identification of the species are shown. This fish has been preserved in a preservative solution and dyed pink.

WHY DO WE MONITOR YOUNG FISH?

Young, small fish are not very good swimmers. Fish start out as eggs that hatch into what are called **larvae**. The larvae are very small and skinny, a few millimeters long in most cases, like the width of a pencil eraser. They are difficult to see! Larvae do not look like adults; they tend to be see-through and lack fins and muscles. During the larval stage, fish drift in the currents. As fish grow larger, they develop muscles and fins that improve their ability to swim. Many also develop air bladders (Figure 1). An air bladder is an organ that fills with air to keep the fish at the right water depth, so that they do not completely sink or float. Eventually, larvae become juveniles, which look like adults but still have growing to do before they can produce eggs. Juvenile fish can ride water currents to areas with beneficial temperatures and food. Many eat small crustaceans called **zooplankton**; when abundant can help the fish grow fast. While riding water currents works well in an estuary where natually flowing rivers and the tidal ocean mix, it can be problematic in modified systems like the San Francisco Estuary (SFE), where humans have changed the amount and direction of water flow, and fish and their food can end up in places they do not belong [1].

LARVAE

Immature or young fish that look different from the adult form of the same species. One fish is called a larva. Larvae refers to more than one immature fish.

ZOOPLANKTON

Microscopic animals that float, drift, or weakly swim with water currents.

The SFE is at the heart of the California water system. This system manages water for both fish and humans. Governments have modified natural waterways to move freshwater to where it is needed. These modifications include dams and reservoirs on rivers to control flows, and export facilities that pump water into canals and pipes. The SFE has many water export facilities, including hundreds of small water pumps for agricultural use, medium water pumps for city drinking water or businesses, and two very large pumps in the south Delta that provide agriculture and drinking water to half the state of California! The amount of water pumped out of the south Delta is so great that the water flow in the rivers can be reversed tens of kilometers away. Fish within the influence of the pumps can easily become captured

ENTRAINMENT

The transport of fish with the flow of water, out of their natural habitat into unnatural or harmful environments, resulting in loss to the population.

[1] https://wildlife.ca.gov/conservation/cesa

(known as **entrainment**), by the export facilities. This is especially true of very small fish and larvae that drift with flows and currents.

To prevent loss of fish by entrainment, scientists and resource managers are interested in knowing where young fish are, to keep them away from the pumping facilities. We are also interested in knowing how many total fish there are, so that we can track their population trends every year, to know how much of the population is at risk of entrainment. This is especially important for fish populations that have declined and now are on state and federal endangered species lists[1]. These native fish require special protections to prevent additional harm to their populations. Sadly, the SFE has many such species, including Delta smelt, longfin smelt, Chinook salmon, steelhead trout, and green sturgeon.

Sampling in a consistent way over time is called monitoring. Monitoring has shown that native fish populations have declined in the SFE. There are many factors that contribute to declining fish populations in addition to water exports and flow changes. These include loss of habitat, predation, competition with introduced species, climate change, and food limitation. Therefore, to understand what we can do for the fish populations, we have to monitor more than just fish abundance. Scientists measure conditions that the fish experience, such as water quality (temperature, salinity, water clarity), hydrodynamics (how fast the water moves and in what direction), climate (wind speed, air temperature), contaminants (pollution), and the food web. Measuring food availability is especially challenging, as it means capturing other very small plants and animals. Scientists look at all these measures, along with the numbers and types of fish that they catch, to understand what influences the increase or decrease of fish populations each year.

HOW DO WE MONITOR YOUNG FISH?

The SFE is a very dynamic system, and the native species are highly adapted to the natural changes. There are over 120 species of fish in the San Francisco Estuary! Since the SFE connects rivers to the ocean, not all fish are present in the SFE all the time. In many cases, the SFE is a migration pathway. This means that fish travel through the SFE on their way upriver or out to sea, but they do not hang around for long periods of their lives. Even species that *do* spend their whole lives in the SFE, like Delta smelt [2], still have seasonal spawning movements. In the spring, during spawning, they are distributed farther upstream, which puts them at higher risk of entrainment. Similarly, species of various sizes are in the SFE at various times. For example, a young Chinook salmon on its way to the ocean is much larger than a young longfin smelt, even when they are both in the same place at the same time. Because the sizes of fish and the seasons they are present in the SFE

Figure 2

Figure 2

A net used to capture larval and juvenile fish in the SFE, called a 20-mm net. It has a rigid mouth frame (mouth area 1.5 m^2), is 5.5 m long, and has mesh holes that are 1.6 mm. A zooplankton net is mounted on top (red arrow), so that fish food can be captured at the same time. Both the fish and zooplankton nets have plastic cod-end jars to concentrate the contents. Contents are poured into sample containers with preservative solution, and returned to the laboratory for processing.

vary among species, we use various types of nets to capture a wide variety of species. It is important to pick the right tool for the job!

One common way of catching small fish is by towing a net through the water (Figure 2). Fishing nets come in various shapes and sizes. The net mouth opening can be large for juvenile fish (15 m^2) or small for larval fish (0.4 m^2). The net mesh openings retain fish of a certain shape and size. For example, nets with very small holes in the mesh (1.6 mm) capture small, larval fish, whereas nets with larger holes (12.7 mm) capture larger, juvenile fish. Catching small fish can be challenging, because small mesh openings will let less water through, thus slowing the net in the water. When the net is moving slowly, large fish might be able to swim out of the net! **Net efficiency** means matching the size of the net mesh to the size range of the fish we want to catch. When the net is hauled out of the water, all the fish are concentrated at the end of the net, called the **cod-end**. The cod-end can be made of soft mesh or a hard box or bottle (Figure 2).

Larger fish can be identified and measured on the boat and released alive, whereas smaller fish are kept in sample jars. Small fish and zooplankton are fragile and must be fixed and preserved using a solution that prevents them from decaying or falling apart when we handle them. Fish samples are taken to the laboratory to be measured and identified under a microscope [3]. Identification of small fish from around 5–50 mm **fork length** (approximately the width of a pencil eraser to the width of two quarters side-by-side) can take 8–20× magnification. Tweezers are used to count the muscles (**myomeres**), fin rays, or length of gut tracts, and to help us see other unique features that allow us to identify the species (Figure 1). Sometimes, small fish are even dyed pink to make them easier to see.

HOW IS THE DATA USED?

In the SFE, the species of greatest concern for managers, particularly those on endangered species lists, are mostly **pelagic**, meaning they

NET EFFICIENCY

A trawl net's ability to catch fish of a specific size and shape.

COD-END

The narrow end of a fish catching trawl net that collects and concentrates the fish. This portion of the net is usually opened to remove the fish.

FORK LENGTH

The measure of a fish from the tip of the head to the fork in the tail.

MYOMERE

Muscles in fish that form a V (or sometimes W) shape and are easy to see on larval fish. Myomere counts are often used to identify a larval fish. See Figure 1.

PELAGIC

Open-water, not near the shore or bottom.

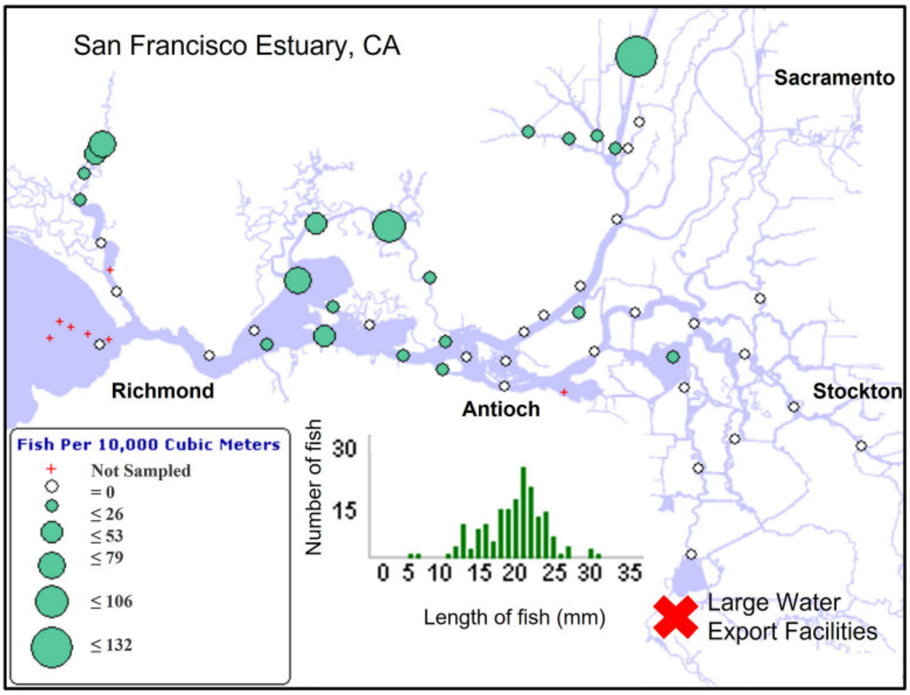

Figure 3

Figure 3

An example of data showing Delta smelt distribution and relative abundance in the SFE, from a survey done with a 20-mm net. Green circles show where fish were captured and the number of fish per volume of water. Larger circles mean more fish were captured. The center graph shows the number fish of each length that were captured. Approximate city locations and locations of large water export facilities (red X) are also shown.

live in open-water habitats. Data from towed nets includes the amount of water sampled. Scientists relate the amount (volume) of water sampled with the fish catch in each tow, then they combine catch data from all the tows in an area (bay or river). These data can then be scaled up to represent the total amount of water in an area, which allows us to estimate the abundance of fish. By looking at specific sampling locations, we can determine how much of the fish population is in "safe" areas where they can grow and survive, and how much is in areas near pumping facilities that could cause population loss.

Keeping fish populations safe requires both short-term and long-term management. Short-term management involves reviewing conditions and monitoring data each week, to make recommendations to modify water flows or change the amount of of water that is exported. Once we get a picture of where the fish are and how many are present, we can adjust water flows so that they are the most beneficial for fish (Figure 3). Long-term management requires the continuous collection of monitoring data and frequent special studies. Many experts are needed to analyze the data and to answer questions about how the water system is functioning and how each species is affected by changing conditions.

MONITORING TO ADVANCE FISH CONSERVATION

The SFE is a complex and busy place! Humans have significantly altered this system to provide water for multiple uses, including drinking water and agriculture. These changes have altered the habitats of the plants and animals that live in the SFE, causing several fish species to become endangered. Monitoring fish populations is extremely important to help with the recovery of endangered fish species. Monitoring allows the comparison of current and past conditions, so that water resources can be managed in a way that best meets the needs of fish and the habitats they rely upon. With proper management, the SFE can be a safe and healthy place for fish to live, while still serving as an important water supply for all of California.

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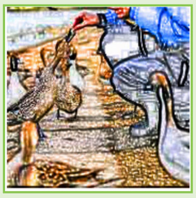
YOUNG REVIEWERS



SCUOLA EUROPEA DI VARESE, AGES: 12–13

These young, very international and a little crazy scientists love to discover the world around them! They are a great team and managed to collaborate successfully on the review of the manuscript!

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Lauren Damon is a senior fisheries biologist with the California Department of Fish and Wildlife. Her work focuses on the response of native fish to habitat changes during the reproductive portion of their lives, especially in response to natural and artificial flow alterations. She is also passionate about mentoring teenagers and young adults who are exploring interests in aquatic or marine ecology. When not working, she enjoys spending time with her daughter and two dogs, taking them outdoors as much as possible, especially swimming or stand-up paddle boarding in rivers, lakes, and the ocean! *Lauren.Damon@wildlife.ca.gov

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Steven Slater is a senior fisheries biologist of 20+ years with the California Department of Fish and Wildlife. His work has focused on long-term monitoring of pelagic fish and zooplankton communities of the San Francisco Estuary. He leads several studies that describe fish trends relative to habitat conditions and how fish utilize small crustaceans as food. His work also includes understanding effectiveness of fish-sampling techniques and testing new sampling technologies. Steve enjoys camping with his family and exploring California's rivers, lakes, and ocean with his sons.

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DIARY OF WIMPY FISH: HOW TO GROW UP IN A CONSERVATION HATCHERY AND SURVIVE IN THE REAL WORLD

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YOUNG REVIEWERS:

ETHAN
AGE: 8

LANGSTON
AGE: 12

Conservation hatcheries are like luxury fish hotels that raise threatened and endangered fish that are nearing extinction in the wild. Raising fish in the controlled environment of the conservation hatchery usually takes away the issues that caused the population to dwindle in the first place. However, there is one problem: the fish get used to the conservation hatchery and become wimpy, meaning they become domesticated and do not do as well as wild fish in if they are returned to the natural environment. Managing the genes of hatchery fish is one way to block domestication and raise fish that are as close as possible to wild fish. In the San Francisco Estuary watershed, there are conservation hatcheries for the endangered delta smelt and winter-run Chinook salmon. Read on to learn about how these conservation hatcheries help hatchery fish be as tough as possible and survive in the wild.

WHAT IS A CONSERVATION HATCHERY?

When a species is threatened or endangered, it is at risk of becoming extinct. Extinction means that an organism disappears forever. If we see that a species is dying off, what can we do to stop it from becoming extinct? Unfortunately, this question is coming up more and more. The United States has laws in place (mainly, the Endangered Species Act) to make sure that threatened and endangered species are protected and that there is a plan with specific actions to help the populations improve. One possible action for fish species that are at risk of extinction is to raise them in a conservation hatchery, or luxury fish hotel, and later release them into the wild. Conservation hatcheries[1] are different from production hatcheries[2]. The goal of production hatcheries is to make as many fish as possible for food or fishing. Instead, the goal of a conservation hatchery is to raise fish that are as similar as possible to wild fish of the same species, but in a controlled environment. This is done so that hatchery fish can survive and mate when they are released into the wild. This may sound easy, but most hatchery fish do not do well in the wild.

[1] See https://restorationfund.org/programs/hatchery/ or https://www.fws.gov/fisheries/nfhs/imperiled_species.html.

[2] See https://www.fws.gov/fisheries/nfhs/fish_production.html.

THE DOMESTICATION DILEMMA

Have you ever gone on a long vacation that was so fun and relaxing it was hard to go back to the stress of school and everyday life? This is what happens to fish that are raised in a hatchery. In the wild, fish are always dealing with changing environmental conditions, like how cloudy the water is and changes in water temperature. Conditions can be different by the month, day, or even hour! Fish in the wild must also watch out for predators like large fish and birds, all while making sure to find enough food. It is much different in the hatchery. The hatchery environment is like a fancy resort with a private chef who serves all-you-can-eat meals, located on an island with mild water temperatures year-round and no bullies (predators) allowed. Fish can live for many **generations** in the hatchery and they get used to the easy hatchery lifestyle. This adaptation to the hatchery, called domestication, can make it very difficult for the fish to return to the harsh natural environment because they have become, well, wimpy [1].

GENERATION

A group of individuals born and living at about the same time. Within your family, your grandparents are one, your parents are a second, and you are a third generation.

What can we do to limit domestication and toughen fish up to prepare them to return to the dog-eat-dog world of the natural environment? One option is to raise fish in tanks that look like wild habitats, with plants, rocks, and other natural features to encourage more natural behavior [2]. We can also train fish to avoid predators, like a self-defense class. The hope is that one or more of these changes will lead to higher survival in the wild. However, the most important thing a conservation hatchery can do to boost survival is called **genetic management**.

GENETIC MANAGEMENT

Specific actions taken by humans to maintain genetic diversity and avoid inbreeding in a population, so that the population can succeed over time.

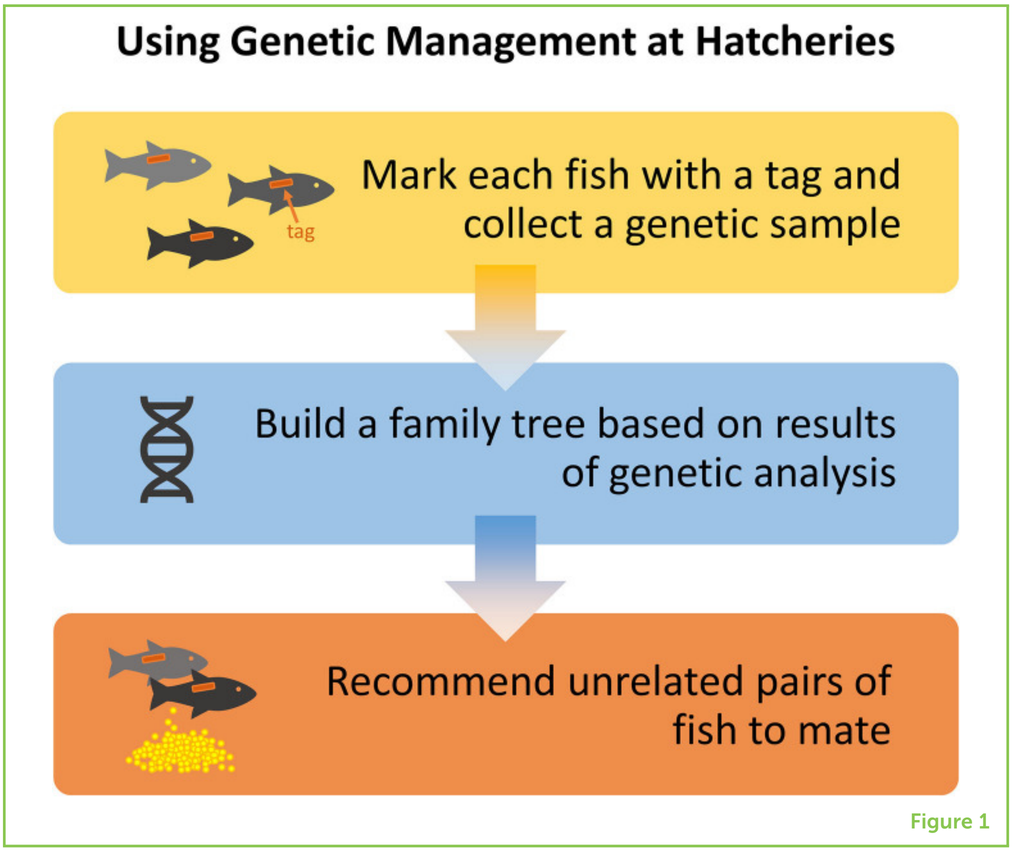

Figure 1

To help maintain genetic diversity in conservation hatcheries, fish receive a special tag and are genetically analyzed. Based on the results, decisions are made about which fish should be mated together. The goal is not to mate fish that are close relatives, to avoid inbreeding. Inbreeding can result in a loss of genetic diversity, which can make fish wimpy.

CONSERVATION HATCHERIES USE GENETIC MANAGEMENT

You have probably heard of DNA and how it contains the code for all your physical traits, like your height and eye color. What you may not know is that every population has a unique genetic signature that is shared by individuals in that population. Over generations, the genetic signature of fish that live in the easy, constant hatchery environment will be different from fish that live in the wild. Also, by only taking a portion of fish from the wild population, there will be less **genetic diversity** in the hatchery population compared to the wild population. Genetic diversity is important for a population because populations with more genetic diversity have a bigger "toolkit" for survival and responding to their environment.

GENETIC DIVERSITY

Variation in DNA among individuals or populations. For example, differences in human eye color and butterfly wing color depend on genetic diversity.

Genetic management can be done in many ways, but the idea is to mate fish that are not related to each other, to try to keep genetic diversity high. The goal of genetic management is to make fish that are better prepared to survive in the wild. To do genetic management, a small tag with an ID is inserted into the fish and then a tiny piece of a fish's fin is taken for genetic analysis. The DNA from the fin sample tells us the fish's family tree, and which other fish would be good mates (Figure 1). More wild fish can also be brought in as mates to "refresh" the genetics of the hatchery population.

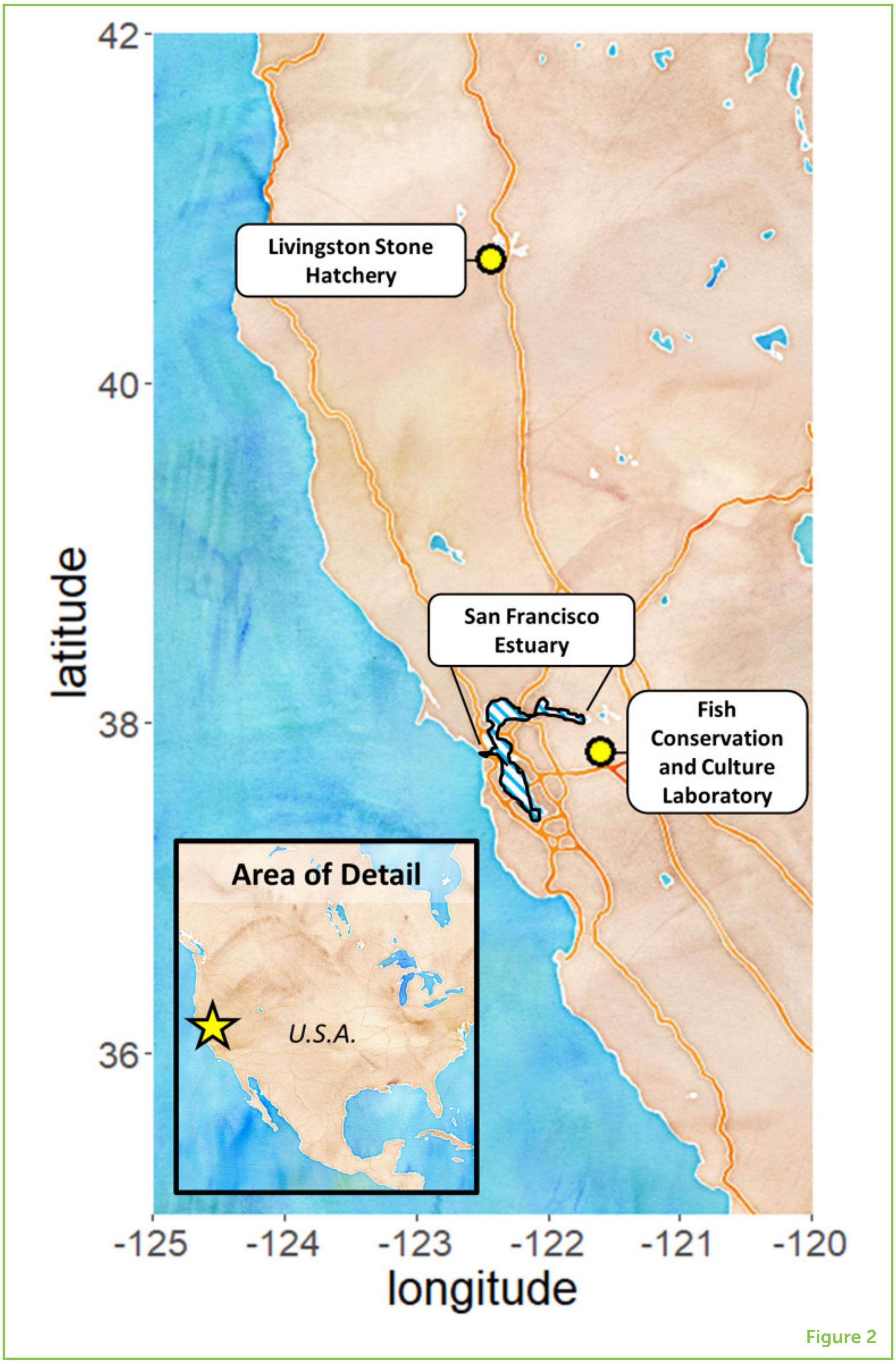

Figure 2

Conservation hatcheries and the San Francisco Estuary. The Livingston Stone National Fish Hatchery is located at the base of Shasta Dam, along the Sacramento River. The Fish Conservation and Culture Laboratory is located east of the San Francisco Estuary, next to the pumps that send water from the Estuary down to central and southern California.

DELTA SMELT, A SMALL WIMPY FISH

Right now, there are two fish species that can only be found in the San Francisco Estuary and are being raised in conservation hatcheries: delta smelt and winter-run Chinook salmon (Figure 2).

The delta smelt is a small (<3 inches), silvery fish. They typically live for just 1 year and if you get really close to one, they smell like cucumbers! Unfortunately, humans have changed the Estuary through pollution from farming, the introduction of non-native species, and by pumping water out of the Estuary. These changes make it harder for native species like delta smelt to live there. There are now so few delta smelt that they are classified as endangered under the California Endangered Species Act. In 2006, a conservation hatchery for delta smelt called the Fish Conservation and Culture Laboratory ("Fish Lab")[3] was built to prevent extinction, even if delta smelt disappear from the wild.

[3] https://fccl.ucdavis.edu/.

The Fish Lab uses genetic management to maintain a healthy population of delta smelt and avoid domestication [3]. Every year, wild delta smelt are captured and mated with delta smelt from the hatchery, to keep the genetic signatures of the two populations as similar as possible. Also, genetic analysis is done so that only unrelated males and females are mated, to make sure that genetic diversity is not lost by **inbreeding**. Today the Fish Lab is in its 14th generation of delta smelt, and this hatchery population is needed more than ever as the wild population grows smaller and smaller. Thousands of acres of tidal wetland habitat are being restored to help create a better home for the species. The Fish Lab is also preparing to make thousands more delta smelt, so that they can be released to supplement the wild population in the next few years.

INBREEDING

Breeding between close relatives. Over time, inbreeding can reduce genetic diversity, which can have negative consequences.

WINTER-RUN CHINOOK SALMON, A LARGE (NOT SO) WIMPY FISH

Chinook salmon are found in the northern Pacific Ocean and range from the Central Valley in California, north along the coast of Canada and Alaska, all the way to the western Pacific. This species can grow to be very large (up to 5 feet!) and is popular with fishermen because of the delicious and nutritious meat. Chinook salmon hatch from eggs in freshwater streams, swim out to the ocean, and then return to the same freshwater streams to spawn (reproduce). The season in which Chinook salmon migrate back to freshwater is called a "run." There are four Chinook salmon runs in the Central Valley: spring, fall, late-fall, and winter. In the past, there were large numbers of winter-run Chinook salmon in the Sacramento River and tributaries. However, the building of the Shasta and Keswick dams in the 1940s blocked these fish from reaching their natural spawning streams. Since then, winter-run have only been able to spawn below the Keswich dam, where the water temperatures are too warm for most eggs to survive. Winter-run numbers are now so low that these fish are listed as endangered under the federal Endangered Species Act.

To boost numbers of winter-run, a conservation hatchery program was started in 1991. Today, wild fish are caught and mated at the Livingston Stone National Fish Hatchery at the bottom of Shasta Dam.

Figure 3

Conservation hatcheries are just one part of saving species from extinction. Poor habitat conditions in the San Francisco Estuary led to the decline of delta smelt and winter-run Chinook salmon populations. While conservation hatcheries can protect these endangered species and eventually reintroduce them into the wild, habitat improvements must also be performed to help species recover.

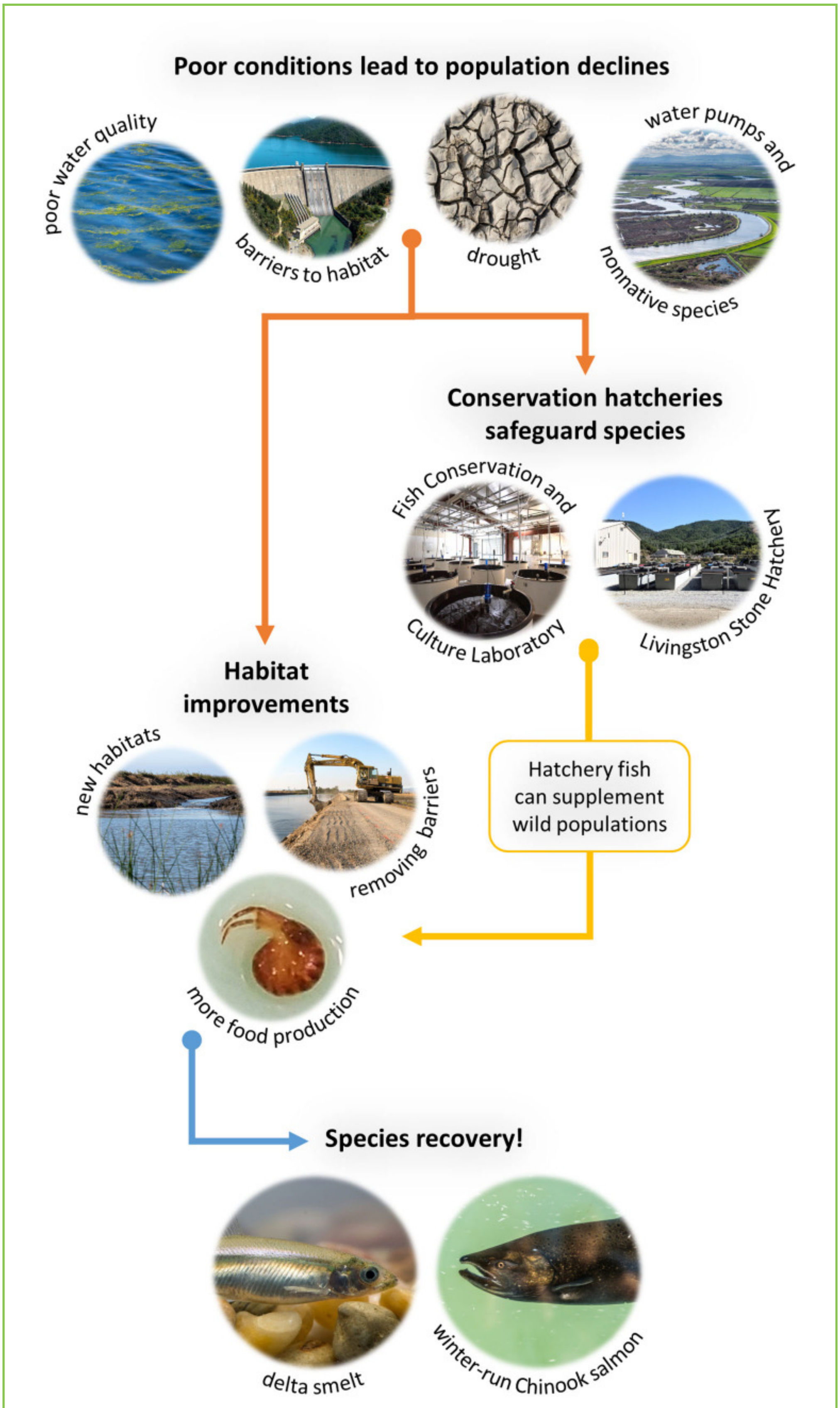

Figure 3

The offspring from these matings are raised in the Hatchery and then returned to the Sacramento River and other associated streams as young fish. Much like at the Fish Lab, genetic analysis tells the Hatchery staff which fish are unrelated and can be mated together to limit domestication, loss of genetic diversity, and inbreeding. However, the Hatchery uses a mating strategy in which eggs from one female are separated into two groups and mixed with the sperm from two different males individually. Doing matings this way can capture even more genetic diversity than matings with a single male and female. While no salmon can truly be called wimpy, hatchery salmon typically do not survive and reproduce as well in the wild as do wild salmon [4]. There is still a long way to go, but conservation hatchery programs have helped stop the extinction of winter-run Chinook salmon.

A RAY OF HOPE

While conservation hatcheries are a useful tool, these hatcheries alone cannot save a species from extinction. Instead, these hatcheries should be used along with other tools and strategies, like creating better habitats and fixing the problems that led to the species decline in the first place (Figure 3). By working together and using conservation hatcheries wisely, we can find ways to keep endangered fish from vanishing completely. Preserving fish species is critical because they are an important part of our ecosystems.

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YOUNG REVIEWERS

ETHAN, AGE: 8

My name is Ethan. I play the piano and take martial arts classes. I like science and to read. My favorite thing to do is to celebrate my friends' birthday parties and to play soccer with my team. I have two miniature Holland Lop bunnies. I love sharks and when I am old, I want to be a conservation biologist.

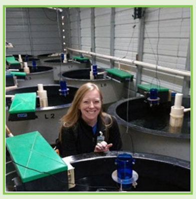
LANGSTON, AGE: 12

My name is Langston and I am 12 years old. Some of the things I like to do include playing sports and video games. My favorite subject is math. When I grow up I want to be an architect.

AUTHORS

AMANDA J. FINGER

I am a research scientist at University of California, Davis. I enjoy thinking about how threatened and endangered populations have changed over time, and I use genetics to answer questions about why populations are the way that they are, and how we can protect them for future generations. My preference is to work with aquatic species, because unlike birds and land animals, we know that they are in water so they are easier to find! When I am not working, I enjoy traveling the world, rock climbing, and puttering around my home in Sacramento, California. *ajfinger@ucdavis.edu



DAPHNE A. GILLE

I am an environmental program manager at the California Department of Water Resources. In my job, I spend a lot of time thinking about how science can be used to better our understanding and help our management of threatened and endangered species. I work as part of a large team of scientists that monitors the health of the San Francisco Estuary by looking at changes in fish populations and water quality. In my free time, I enjoy spending time with my family, hiking and camping in our coastal redwood forests, and making and eating pie!

NICOLE M. KWAN

I am a fisheries ecologist with the California Department of Water Resources. I am passionate about helping advance fisheries science to help native species in decline. At work, I often put on waders and head out into the field to sample fish in river and floodplain habitats. The data from these sampling projects are an important part of monitoring native and endangered species and informing actions to improve their populations. In my free time, I enjoy running with my dog, doing DIY projects, and traveling.

MELINDA R. BAERWALD

Two things I feel passionate about are the conservation of threatened species and learning new things about our world through science. I am lucky because in my job as an environmental program manager for the California Department of Water Resources, I get to do both! I like to use genetic approaches to aid species and my research projects have focused on topics such as migration, predation, and disease. My dream species I would love to study is the mountain gorilla. In my free time I like to hike, garden, read, and visit the ocean.

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USING CONSERVATION PLANNING TO CREATE THE PERFECT HOME FOR DUCKS

Keiko Mertz [1*], ***Aviv Karasov-Olson*** [2], ***Cliff Feldheim*** [3] ***and John Eadie*** [1]

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YOUNG REVIEWERS

SCUOLA EUROPEA DI VARESE

AGES: 11–12

Did you know that many birds use the San Francisco Estuary like a hotel, to rest during their long migrations? The Estuary is a major stopover on the Pacific Flyway—a huge path for migrating birds that runs from South America to the Arctic Circle! Tons of waterfowl (ducks, geese, and shorebirds) make this journey every year. On this long, harsh journey, birds need to find food and safe places to rest. In the U.S., many groups work together to manage habitat to help these birds have a successful journey. Surprisingly, each species of bird has different needs, so managers must make plans for the whole landscape to take care of them all! In this article, we will explore the concept of conservation planning for waterfowl using the San Francisco Estuary, with special focus on the unique needs of mallards, canvasbacks, and surf scoters.

WHAT IS CONSERVATION AND WHY IS IT IMPORTANT?

Conservation is the care and protection of nature and wildlife. The goal of conservation is to ensure a healthy environment for all living things, far into the future. You may have already heard of conservation of endangered **species** like polar bears, sea turtles, and tigers. We also conserve animals to ensure that they never *become* endangered. We can protect animals, for example by putting cages around sea turtle nests to prevent other animals from eating the eggs. Other times, conservation requires protecting **habitat**. Habitat is the place an animal gets food, water, and shelter.

CONSERVATION

Care and protection of plants, animals, and the environments in which they live.

SPECIES

A group of living things that share the same name and can reproduce with each other.

HABITAT

The home of an animal, which provides the animal with everything it needs to live: food, water, and a place to rest/sleep.

Humans conserve things for three main reasons. The first reason is that we believe that what we are conserving is valuable and deserves to exist. We want polar bears to exist because we think their lives have value, even though many of us will never see them in the wild. Second, we might want to conserve something that provides us with a service. For example, we can protect the wetlands near the ocean because they can prevent floods as sea levels rise. Third, humans protect things because they can use them. For example, we conserve national parks like the Florida Everglades so we can visit and enjoy them.

Conservation is complex, so it requires detailed planning. There are many possible solutions to a single conservation problem. For example, to conserve polar bears, we need to conserve their habitat, so they have a place to live. We also need to conserve the seals they eat, and the fish that seals eat! Conservation involves many steps and many decisions must be made along the way. Planning helps conservation **biologists** use as much information as possible to make decisions [1]. When we protect animals over large areas, it is easy to make a mistake. Planning helps us avoid those mistakes.

BIOLOGIST

Someone who studies living things like plants, animals, or bacteria.

WHICH ANIMALS SHOULD WE CONSERVE IN THE SAN FRANCISCO ESTUARY?

The San Francisco Estuary and surrounding wetlands are filled with unique wildlife and their habitats. Some animals, like the salt marsh harvest mouse, live only in the Estuary and nowhere else in the world. Others, like ducks and geese, use the Estuary like a hotel during their long migration journeys. In fact, the Estuary is a major stopover on the Pacific Flyway—a huge migratory path that runs from South America to the Arctic Circle! Millions of ducks, geese, and shorebirds make this journey every year. On this long and harsh journey, birds need to find food and safe places to rest. Biologists work together to give these birds what they need for a successful journey [2].

Mallards, canvasbacks, and surf scoters are three types of ducks that use the Estuary and the connected rivers and wetlands. Conservation planning can ensure that each species of duck gets enough food to survive their long migrations. We will use these three species as our example of how to do conservation planning.

WHAT DO THE DUCKS NEED?

It might be obvious to you that ducks and other animals, like turtles, eat different things. But did you know that different kinds of ducks eat different things (Figure 1)? We will focus on *winter* foods and habitat. When using the San Francisco Estuary as a winter migration stop, ducks focus on building energy to continue their journeys [3]. To get enough energy, mallards hunt for seeds in shallow wetlands by dabbling, or "tipping up" with their tails in the air, to reach seeds on the bottom. Canvasbacks stuff themselves with plant parts like stems and seeds, by diving in deep water. Lastly, surf scoters dive in the ocean for crabs, mussels, and fish eggs.

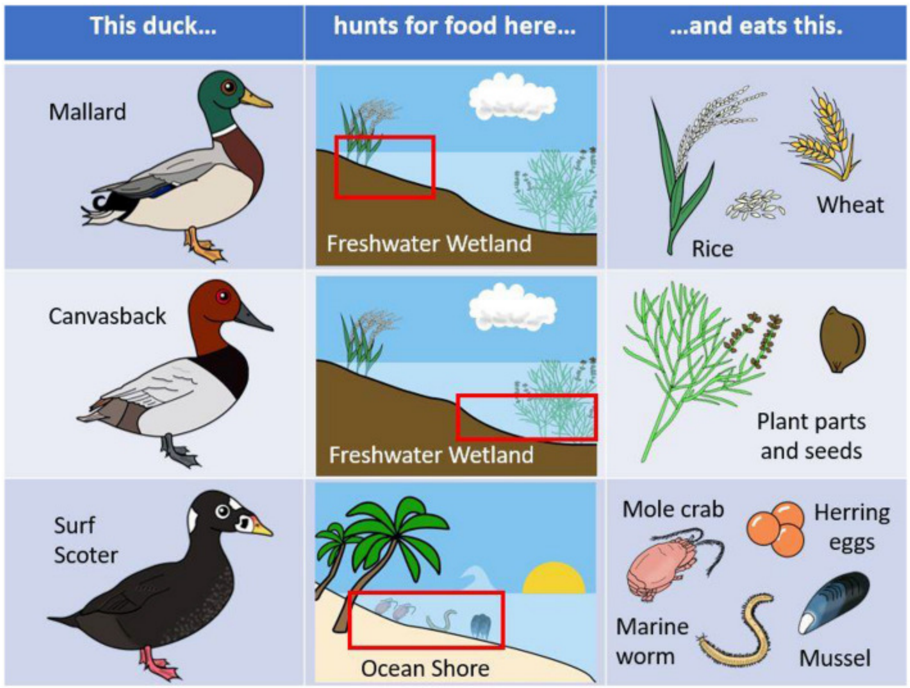


Figure 1

Figure 1

Mallards, canvasbacks, and surf scoters prefer different habitats and different kinds of food.

HOW DO WE MAKE A CONSERVATION PLAN?

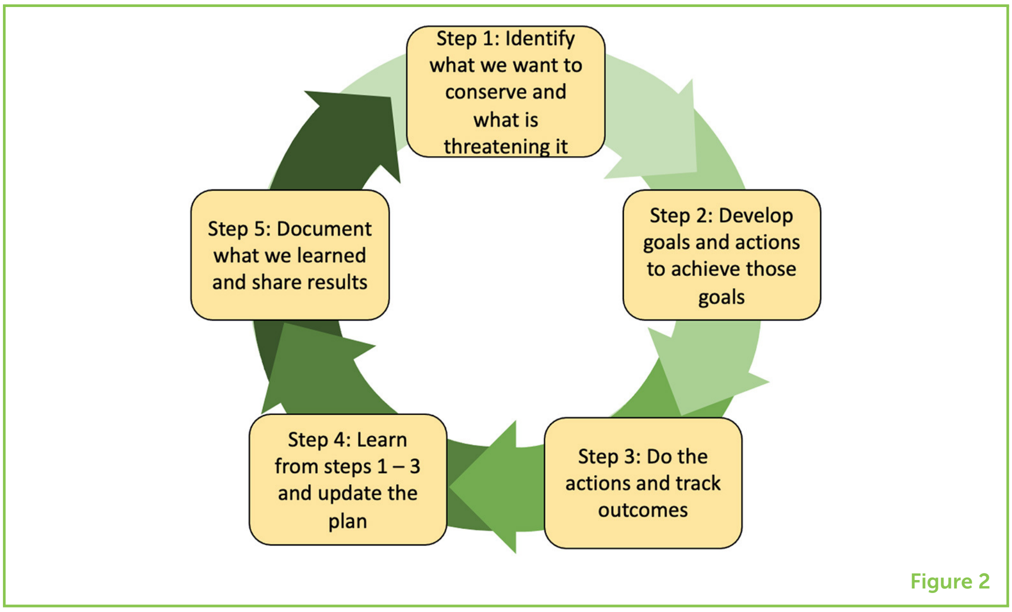
We can plan for all the complex needs of different species by using conservation planning tools. One tool is called the **Conservation Standards** [4]. This tool was created by scientists from many organizations. The Conservation Standards has a special vocabulary that conservation scientists can use even if they work in different areas with different species. There is also a special software designed to help scientists use the Conservation Standards and share their conservation plans with others. This tool has only five steps (Figure 2).

CONSERVATION STANDARDS

Guidelines for conservation to help identify goals, develop and implement a plan, and share results.

Figure 2

Summary of steps involved in conservation planning, adapted from the Conservation Standards.



THREAT

Something that can cause harm, or the ability to cause something harmful.

POPULATION

A group of animals of the same species that live in a certain place.

The first step in the Conservation Standards is to identify what we want to conserve and what is threatening it. In this step, it is important to clearly determine how **threats** are affecting the species we want to conserve. In our example, we want to conserve mallards, canvasbacks, and surf scoters that use the San Francisco Estuary and nearby wetlands. Remember that each duck eats different foods. One threat to each species is the loss of these foods. Mallards prefer seeds and some agricultural foods like rice and wheat. Their food is affected by which crops farmers grow in and near wetlands. Canvasbacks prefer plants like pondweed, which depend on the amount of water in a pond or wetland. Surf scoters love clams and mussels, which can be managed in protected marine areas.

The second step is to develop goals and actions we can take. Our goal is to have healthy **populations** of these three species. Many actions can accomplish that goal. We can work with wetland managers to ensure they grow the right foods at the right times, to provide food like rice and wheat for mallards. In California, water is precious. Wetland managers can control water depth in their wetlands. In Figure 1, you can see that canvasbacks dive in deep water to eat. To support canvasbacks, we can work with wetland managers to provide deeper water and lots of plants. To support surf scoters, we can protect the areas of the San Francisco Estuary that contain their favorite foods, like herring eggs. When boats use these areas too much, the birds avoid them and miss out on yummy food! These different actions benefit the needs of each species during winter in the Estuary.

The third step is the fun part! We get do those actions. This part can take a lot of time. Sometimes people must work together to build new habitat, by sculpting the earth and planting the right plants. In this third step, we also create a plan to keep track of how well we are meeting our goals. In our example, biologists would track changes in mallard, canvasback, and surf scoter population sizes.

The fourth step is to learn from the first three steps. In this step, we look back at our actions and check how well they helped us meet our goals. We also look for ways to improve, by coming up with ideas for new actions we could take.

The last step is to share what we learned. We can also think about other actions that might help grow or maintain the populations of these species. Then we can repeat all the other steps again! The steps take us in a big circle because each action is a chance to learn and improve. Also, by sharing what we learned about conservation in our area, we can help other scientists with their conservation projects!

This whole process could never be completed by one person! A major part of conservation planning is teamwork. In fact, solving conservation problems often requires several teams with different expertise, working together. This is like a soccer team: each member of the team has a different role. Only by working together can the team be successful. In the end, the more people helping, the better the outcome will be!

IF YOU PLAN IT, THEY WILL COME: CONSERVATION PLANNING IN THE ESTUARY

Hopefully, you have learned that not all ducks need the same things to survive. Although they have similar needs, there are differences. A planned landscape can support more kinds of ducks, and larger numbers of them, too (Figure 3)! Conservation planning is beneficial to the three duck species we discussed—the mallard, canvasback, and surf scoter. The cool thing is, this tool is not only for ducks! It can be used for other species and habitats throughout the San Francisco Estuary.

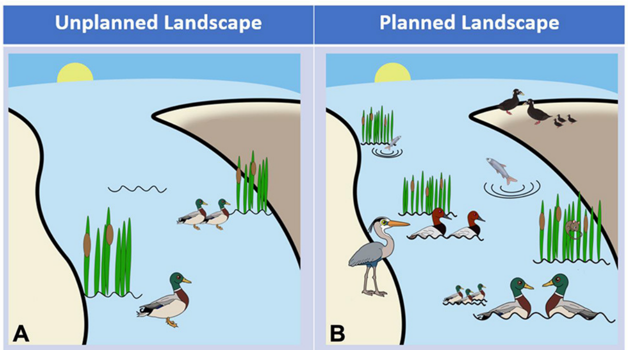


Figure 3

Figure 3

(A) An unplanned landscape does not support very many ducks or very many types of species. **(B)** Conservation planning helps support greater numbers of animals and more types of species.

The San Francisco Estuary is a complex place. Many different teams are working on various projects to create a healthy environment. Conservation planning helps managers choose the best actions and test the success of those actions. Remember, people conserve things for various reasons. Conservation planning helps recognize different values and ensure that all needs are met. In the San Francisco Estuary, this method can be used to conserve habitats like tidal marshes, endangered species like the salt marsh harvest mouse, and migratory birds like the three ducks in our example! Conservation planning can help biologists make the best decisions as efficiently as possible. In the Estuary, conservation planning helps improve habitat and wildlife populations, and it can also help conserve species and habitats across the world!

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YOUNG REVIEWERS

SCUOLA EUROPEA DI VARESE, AGES: 11–12

These young, very international, and a little crazy scientists love to discover the world around them! They are a great team and managed to collaborate successfully on the manuscript.

AUTHORS

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Keiko Mertz is a native Californian with a passion for the environment. She has a master's in environmental policy and management and is working to get her second master's in avian science at the University of California, Davis. She is passionate about making science accessible to everyone, and she is interested in the connection between policy and science. She believes conservation relies on our ability to collaborate, inspire, and communicate effectively. In her free time, she likes to read, do yoga, be outdoors, and express her creativity. *kbmertz@ucdavis.edu

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Aviv Karasov-Olson is a Ph.D. candidate studying ecology at the University of California, Davis. Her research focuses on conservation, climate change adaptation, and how people work together to manage wildlife. She has worked as a field biologist throughout the U.S., with many animals including spotted owls, sea turtles, elk, black bears, and kangaroo rats. She also loves bird watching, reading, and hiking with her dog.

CLIFF FELDHEIM

Cliff Feldheim is an award-winning, nationally recognized waterfowl biologist with over 20 years of professional experience. He completed both his Bachelor of Science and Master of Science degrees in wildlife management at Humboldt State University. For the last 6 years, he led the largest waterfowl telemetry study ever conducted—13 species with cell tower GPS transmitters and over 1,000,000 data points! When he is not working, he enjoys fishing, hunting, bird watching, and spending time in nature with his four children.

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John M. Eadie is a professor in the Department of Wildlife, Fish and Conservation Biology at the University of California, Davis. He holds the Dennis G. Raveling Chair in Waterfowl Biology. He received his Ph.D. from the University of British Columbia and taught at the University of Toronto from 1989 to 1996 prior to his current position at Davis. His research interests include the ecology and management of waterfowl and wetlands. He and his students have studied mallards, wood ducks, goldeneyes, eiders, geese, trumpeter swans, Orinoco geese, and black-headed ducks at study sites ranging from Alaska to Argentina.

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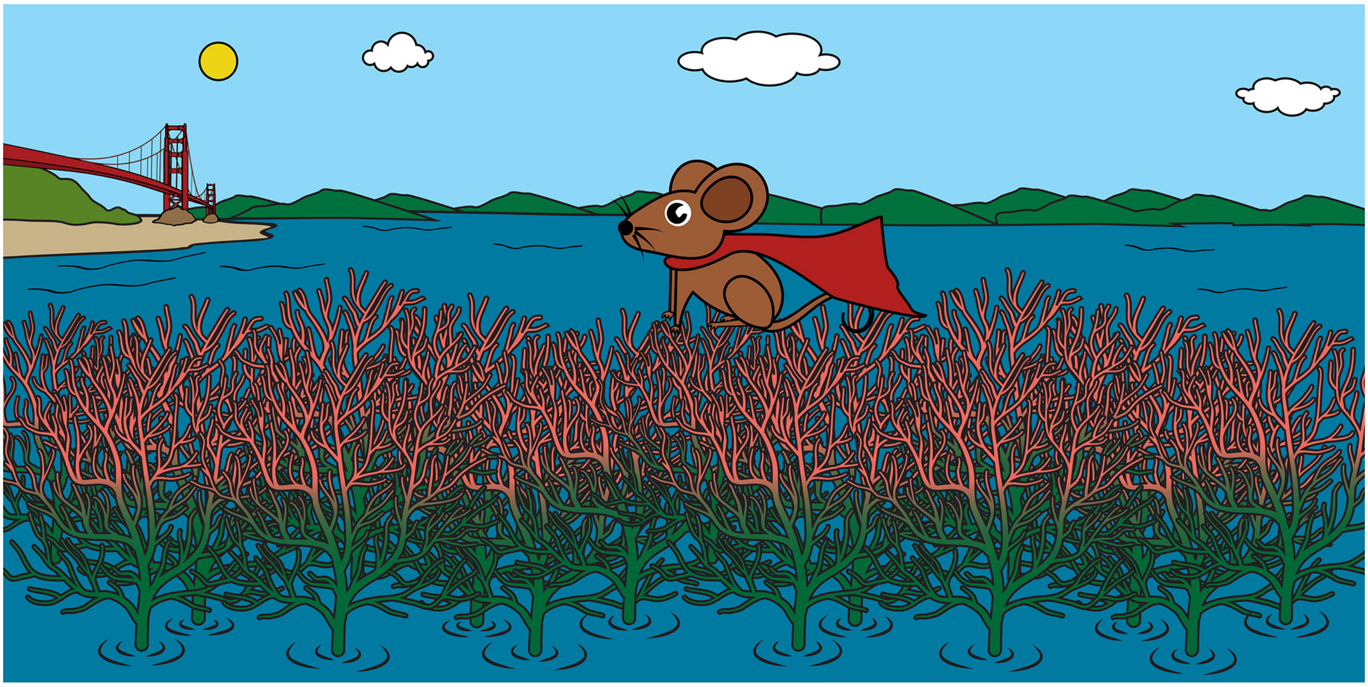

SAVING THE INCREDIBLE SALT MARSH HARVEST MOUSE!

***Katherine R. Smith*[1,2*]*, Melissa K. Riley*[2,3]*, Laureen M. Barthman-Thompson*[4] *and Sarah A. Estrella*[3]**

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YOUNG REVIEWERS

CORTE MADERA SCHOOL

AGES: 10–11

Did you know that one of the most unique and incredible mammals in the world is found only in the San Francisco Bay-Estuary? The salt marsh harvest mouse is an endangered species because over 90% of its coastal marsh habitat has been lost due to human development. This species can swim for over 2h, can climb using its tail like a fifth limb, can eat salty foods, and can even drink water saltier than the ocean! For decades, people thought this animal could live only in tidal marshes dominated by salt-loving plants. However, in the past few years, we have learned many new things about the salt marsh harvest mouse. For example, we now know it can live in non-tidal marshes and forage on freshwater plants. Unfortunately, the superhero abilities of this mouse will not protect it from all the threats it faces in the future, such as sea-level rise.

Figure 1

Figure 1

A salt marsh harvest mouse in a biologist's hand. The marsh and bay can be seen in the background.

AN UNUSUAL MOUSE

The salt marsh harvest mouse (let us call them Salties for short) is the only mammal in the world that lives only in marshes near the ocean. Salties are about the size of a big thumb and weigh about as much as two nickels. They range in color from blond to black, but are usually the color of cinnamon, and sometimes have a bright orange belly (Figure 1). The species is **endemic** to the San Francisco Estuary, which means Salties do not live anywhere else in the world. Humans have changed the Estuary a lot. Over 90% of the **tidal marshes** (areas where waters get higher or lower depending on the ocean tides) where Salties used to live have been converted for housing, business, farming, or other human uses [1]. This huge loss of habitat led both the United States Fish and Wildlife Service and the California Department of Fish and Wildlife to list Salties as endangered in the early 1970's [1]. Since then, biologists have worked hard to understand how Salties are influenced by their physical surroundings and by other organisms, with the goal of protecting their remaining habitat and creating new habitat through tidal marsh restoration.

ENDEMIC

Living only in a certain place.

TIDAL MARSHES

Marshes that have a regular rise and fall in water level due to the movement of the ocean tides.

Even though Salties were discovered in 1908 [1], researchers did not pay much attention to them until the 1960s. Some pretty amazing things have been discovered about Salties. They can swim for more than 2 h without getting tired, use their tails like an extra hand for climbing in vegetation above tidal waters, eat very salty foods, and drink sea water [2]! Biologists thought that the species needed tidal marshes almost completely covered by a short, fleshy plant called pickleweed. However, there was a lot that biologists did not fully understand about Salties at that time. Most biologists only looked for Salties in tidal marshes, and did not look for or find them in areas where tidal waters did not reach. This meant that biologists focused mainly on protecting and improving tidal marshes.

Figure 2

Figure 2

A salt marsh harvest mouse standing inside of a trap before the door closes. This trap was in a non-tidal marsh, so it could be placed directly on the ground without risk of flooding by tidal waters.

MICE IN UNEXPECTED PLACES

In the late 1990s, some curious biologists started looking for Salties in **non-tidal marshes**, where big dirt walls called **levees** kept out the water moved by tides, and they discovered there were many Salties in these marshes [3]! These biologists also learned that Salties like areas with various kinds of plants, not just areas where there is a lot of pickleweed. This came as a surprise to many scientists who thought that Salties could not live in habitats without pickleweed. The new information generated a lot of questions! Are there more Salties in tidal marshes or in non-tidal marshes? Do Salties really require pickleweed for food and nesting? Can Salties live in areas where there is no pickleweed at all? Do these mice use tidal and non-tidal habitats differently when searching for food and nesting?

NON-TIDAL MARSHES

Marshes where tidal waters cannot reach and water levels usually do not change on a daily basis. Non-tidal marshes may be marshes near the ocean with **levees** around them, but they can also be far from the ocean.

LEVEE

A barrier, usually made of soil or rock, that prevents the movement of water.

The answers to these questions are important for deciding which habitats to protect for Salties. There are plans to change some of the non-tidal marshes in the Estuary into tidal marshes, because people think it will benefit Salties. This new information will also help us deal with new challenges, like sea-level rise caused by climate change. For example, biologists need to know whether tidal marshes or non-tidal marshes will be better places for Salties to live as sea levels get higher and higher.

TESTING OUR NEW IDEAS

With this new knowledge and a new set of research questions, biologists designed a bunch of new experiments to study Salties. To understand whether tidal or non-tidal marshes were better for Salties, scientists designed a **long-term study** in both marsh types. Box-like traps containing seeds that the mice like to eat, and a fluffy ball of cotton for them to cuddle in, were used to lure the mice into the traps (Figure 2). These traps were placed in the marsh and opened

LONG-TERM STUDY

A study where repeated observations or measurements are made over a long period, usually months or years.

Figure 3

Figure 3

A salt marsh harvest mouse standing on top of a datasheet with the tracking collar that was just taken off him, to his left. Check out the frayed antenna wires where the mouse chewed on the collar! Also pictured are the various tools that we use to measure Salties and to put on/take off their collars.

at sunset. During the night, if a mouse walked into the trap, a door closed behind it. While inside, the Salty got to feast on a yummy meal and sleep in a comfortable, warm bed until the morning, when biologists returned. First, the biologists gently removed the mice from the traps and measured them. Like all wild mice, Salties sometimes bite biologists, but they are mostly friendly, with soft fur, grippy foot pads, long whiskers, and big eyes and ears. Once the mice were measured, the biologists gave each one a tiny tag on its ear (like an earring!) with a unique number. Then they returned the mice to their nesting areas. By continuing to trap and tag mice in the same marshes, biologists could estimate how many Salties were in each marsh area.

To find out what types of foods Salties like to eat, some of the captured mice were placed into buckets with different jars of food found in tidal and non-tidal marshes, like seeds, leaves, flowers, and even beetles and tiny shrimps! Those mice were video recorded while they ate the different foods, to see which foods they spent the most time eating.

Finally, some of the Salties that were captured were given tiny collars with tracking devices on them before they were set free (Figure 3). For the next 2 weeks, biologists followed the mice around and recorded where they ate at night and slept during the day.

OUR INTUITIONS WERE RIGHT!

Through these studies, biologists found a similar number of Salties in tidal and non-tidal marshes. This means that non-tidal marshes are also good habitat for the species [4]. Results of the food preference study showed that Salties will eat many different types of plants and bugs from both marsh types. They did like pickleweed—the food everyone thought was their favorite—a lot, but there were other plants they liked just as much, like fat hen and rabbitsfoot grass, both of which are commonly found in non-tidal marshes [5]. Finally, Salties in the tracking study moved around a lot in their habitats, crossing over levees between tidal and non-tidal marshes, and even sometimes moving into **upland** areas. Some mice moved just a few meters each night, while some ran hundreds of meters from one side of the marsh to the other, several times a night. Salties also built nests in many different types of plants, not just pickleweed, and used old bird nests and burrows dug by other animals, like crayfish. This showed that Salties have a lot of flexibility in how they use their habitat. They do not need to live their entire lives in tidal marshes with lots of pickleweed, as biologists believed for many decades [4, 6].

UPLAND

Habitats that are elevated above water level. In the San Francisco Estuary these are often dry and grassy, and near tidal marshes.

While in some ways this is good news, it also makes conserving Salties more complicated. There are plans to convert non-tidal marshes to tidal marshes throughout the Estuary, in part to benefit Salties. But will this restoration benefit the species if there are similar numbers of Salties in both types of marshes? Biologists are now more carefully considering the value of non-tidal marshes. As before, this new information has opened the door to a whole new set of research questions. One of those questions is: if Salties are flexible in their habitat and food requirements, why do they live only in marsh areas? With their ability to swim and drink saltwater, Salties can live in marsh habitats more easily than other rodents can. In upland areas, other rodents probably bully the Salties, and there are a lot more predators. New research supports the possibility that Salties avoid moving out of flooded marshes into uplands where there are lots of other rodents. So how do other species affect Salties?

SALTIES ARE PART OF A COMMUNITY

For decades, researchers have studied Salties without considering the larger wildlife community, including other rodents (competitors) and animals that eat mice for food (predators). We still have many questions about how other species might affect our efforts to protect Salties. For example, if we build islands so that Salties can move to high ground during floods, will the dry soil on the islands allow competitors like deer mice to dig burrows and take over? Or, will building more uplands near marshes for Salties to use during flood events create a path for predators like gray foxes, coyotes, and even cats to access marsh habitat and eat Salties? No conservation action should be taken without considering how all animals in the marsh community might affect outcomes.

Though biologists have learned a lot about Salties over the years, you can see that there are still a lot of unknowns when it comes to habitat protection, enhancement, and restoration. These unanswered questions stand in the way of increasing populations of Salties to levels where they can be taken off the endangered species list. As the risks of climate change and sea-level rise grow, it is even more important to keep researching this species. It will take a new generation of biologists to keep searching for answers to the many questions about Salties that still remain; and answering one question often leads to infinite new ones! Will YOU be the next champion for this awesome creature and help make sure they stay in our marshes forever?

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YOUNG REVIEWERS

CORTE MADERA SCHOOL, AGES: 10–11

We are a fifth grade class, excited about all things science. Since we live in the San Francisco Bay Area, we love to learn about the amazing wildlife and the natural environment around us.

AUTHORS

KATHERINE R. SMITH

Dr. Smith has been studying the salt marsh harvest mouse for over a decade and devoted her master's and Ph.D., work to improving conservation of the species. She loves all rodents, and especially likes to study their behavior to better understand how they use their habitats. Dr. Smith worked for California Department of Fish and Wildlife for about 10 years while she was doing her graduate school research. She is now a wildlife biologist at WRA, Inc. an environmental consulting firm, and helps her old lab at University of California, Davis with mouse research. Most nights you can find her lurking in the marshes around the bay. *ratsmith@ucdavis.edu; ksmith@wra-ca.com

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Melissa Riley is an environmental scientist at the California Department of Fish and Wildlife. She received her bachelor's degree from University of California, Berkeley, where she first started researching land use change and its effect on wildlife. Since 2012, Melissa has worked at California Department of Fish and Wildlife on a team researching wildlife species like western pond turtles and salt marsh harvest mice. She is also pursuing her doctorate degree in ecology at University of California, Davis, focusing on western pond turtle habitat use. She is interested in studying the effects of tidal restoration and land management on turtle and mouse populations.

LAUREEN M. BARTHMAN-THOMPSON

Laureen is an environmental scientist with the California Department of Fish and Wildlife, Bay Delta Region. She has over 25 years of experience working with small mammals, performing terrestrial wildlife inventories and scientific research projects. She is the co-lead for the a group working on the endangered salt marsh harvest mouse. She works with many other agencies on Suisun Marsh planning, permitting, and monitoring. She has coauthored 7 peer-reviewed papers, presented several professional talks, obtained 5 major grants, and contributed to several collaborations. She has a B.Sc. in wildlife and fisheries biology from University of California, Davis.

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Sarah has been a wildlife biologist for 21 years. She holds a B.Sc. from the University of California, Davis, and M.Sc., from California State University, Sacramento. She works with endangered plant and animal species recovery and habitat restoration in the San Francisco Bay and Delta.

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HOW WETLAND PLANTS DEAL WITH STRESS

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YOUNG REVIEWER:

KONSTANTIN
AGE: 15

We all get stressed. To deal with that stress, some of us may exercise, take a bubble bath, cry, or simply leave the stressful situation. But how can you cope with stress if you are rooted in place? Plants that live in estuaries are exposed to many types of stresses from the environment, including flooding, high salt levels, low soil oxygen, and waves. Fortunately, wetland plants have developed ways to survive within these conditions, from excreting salt, to growing faster, to even breaking down cell walls to maximize air flow. Plants can tolerate different levels of stress depending on their age and species. Knowing how plants react to stress is important for our understanding of nature and for managing important environments, like wetlands! This article explores how plant species in the San Francisco Estuary react to stress and how we can use knowledge about plant stress responses to protect wetlands.

LIFE IN A WETLAND—A PLANT'S PERSPECTIVE

When you think about the San Francisco **Estuary**, or any wetland for that matter, what comes to mind? Perhaps a serene landscape with

ESTUARY

The mouth of a river, where freshwater from the river meets salty water from the ocean.

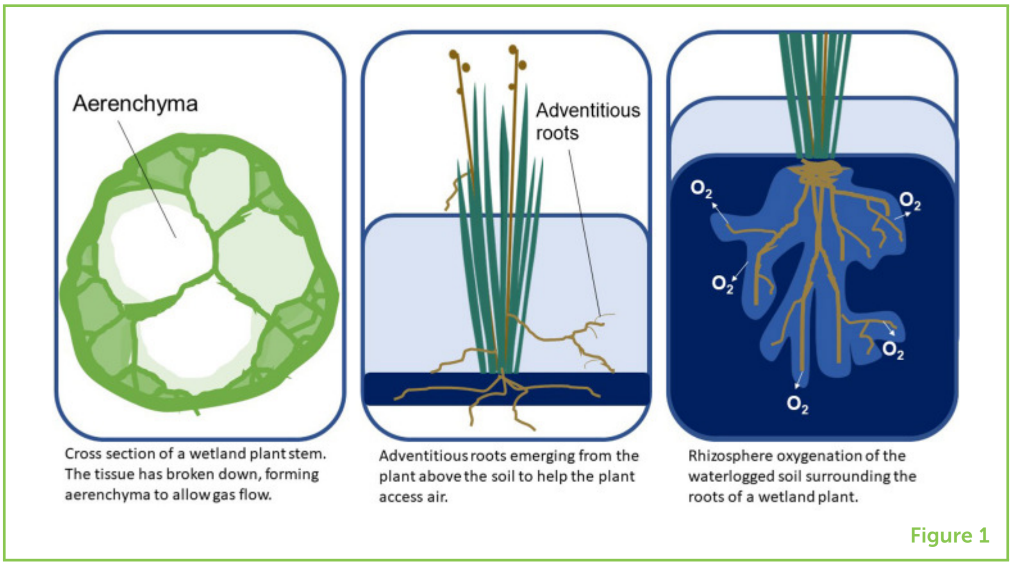

Figure 1

Wetland plants use several adaptations to respond to flooding stress, including air pockets called aerenchyma, special roots above the soil called adventitious roots, and structures that release oxygen into the soil around the roots (Image credit: IAN Image Library, 2020).

blue water trickling by, the evening songs of a red-winged blackbird, the humming of insects, and the laughter of a family fishing from a canoe. The word "stress" probably does not come to mind. However, for a plant, this scene presents several **stressors** that make survival and growth difficult. There are more than 391,000 species of plants on the planet [1], and although all plants need some water to survive, most of those species cannot survive being flooded for long periods of time. Flooding is only one of many stressors that a plant may have to overcome while living in an estuary; it is also stressful for plants to deal with changing amounts of salt in the water, with low levels of oxygen in the soil.

STRESSORS

Features of the environment that may create conditions that are difficult for biological organisms to survive in.

Although most plants cannot handle the stress of living in a coastal or estuarine environment, some plant species have special **adaptations** to help them survive these conditions; we call them wetland plants. Wetland plants all have one thing in common: they live in wet places. But there are many different species of wetland plants, including grasses, trees, and plants that live on top of or underneath the water, all of which have different adaptations to deal with stress [2]. Importantly, plant species differ in how they overcome stress and what level of stress they can handle.

ADAPTATION

A change in a feature or process that makes an organism better suited to live in its surrounding environment.

FLOODING STRESS—HOW FLOODED PLANTS KEEP FROM DROWNING

Plants living in wetlands are either floating on top of the water, submerged underneath the water, or rooted in soil that is flooded at least part of the year. When flooded, plants may have limited access to the sunlight needed for growth, and their soils may have less oxygen needed for the roots. This makes survival, **photosynthesis**, and growth difficult, so wetland plants have evolved adaptations to cope with living in flooded places [3] (Figure 1).

PHOTOSYNTHESIS

The process plants use to make sugar (food) from light, water, and carbon dioxide (CO_2).

One way that wetland plants may overcome flooding and low-oxygen conditions is by forming **aerenchyma** in their stems and root tissues. Aerenchyma are air spaces that allow the plant to move air and oxygen from above the water into its roots. These air spaces may be something the plant always had, or they may form due to a chemical reaction that breaks down cells in response to how long the plant is flooded. Therefore, a plant living in a dry place may have less aerenchyma than a plant of the same species living in a wet place [4]. Testing differences in aerenchyma between plants grown in flooded vs. non-flooded places allow us to understand how plants can respond to the stress of being flooded.

AERENCHYMA

A soft plant tissue, often found in wetland plants, that contains open spaces to increase air flow under flooded conditions.

Other wetland plants deal with low-oxygen soils and flooded roots by producing roots above the soil or even above the water line. These roots, which may come out of the plant's stem, are called **adventitious roots**. Unlike most animals, plants can create almost any structure from almost any cell on their bodies. This is why you may occasionally see roots growing from the stem! Other wetland plants cope with flooded soil by limiting where their roots grow. For example, these plants may only produce roots at shallow soil depths, to avoid the low-oxygen conditions present deeper in the soil. Some wetland plants will use their roots to make their surroundings more comfortable. These plants use a process called **rhizosphere oxygenation**, in which they release oxygen from their own roots into the surrounding soil, which makes living in that soil less stressful. Finally, other plants have adapted mechanisms to escape the stress of flooding by rapidly growing their stems above the water. By keeping a portion of the stem out of the water, the plant can continue to photosynthesize and access air.

ADVENTITIOUS ROOTS

Roots that form from a non-root part of the plant due to either normal development or in response to stress.

RHIZOSPHERE OXYGENATION

The process by which the roots of a flooded plant leak oxygen into the waterlogged soil.

SALINITY STRESS—HOW PLANTS MAKE THE BEST OF A SALTY SITUATION

Although flooding may be a stressful component of all wetlands, coastal and estuarine wetlands have a major additional stress to deal with—salt! In estuaries, inland freshwater drains into the ocean. Fresh water is mixed with salt water and, depending on tides and seasonal weather patterns, the **salinity** of the water may change throughout the estuary. Most of the world's plants, and even many wetland plants, cannot survive being exposed to salt. Salt can slow plant growth and even cause death.

SALINITY

The amount of salt dissolved into water.

However, some plant species living in California's San Francisco Estuary have adapted mechanisms to avoid, exclude, or excrete salt (Figure 2). For example, pickleweed (*Salicornia virginica*) is a plant species that can avoid salt stress by filtering out salt and pumping it out of the roots. For other plants, like smooth cord grass (*Spartina alterniflora*), the leaves remove the salt that enters the plant's body [5]. Coastal plant species, like *Batis maritima,* put the salt into a special

Figure 2

Wetland plants use several adaptations to deal with salt (NaCl) stress, including preventing salt from entering the roots (exclusion), discharging salt from the leaves (excretion), or concentrating salt into a leaf which is later dropped from the plant (Image credit: IAN Image Library, 2020).

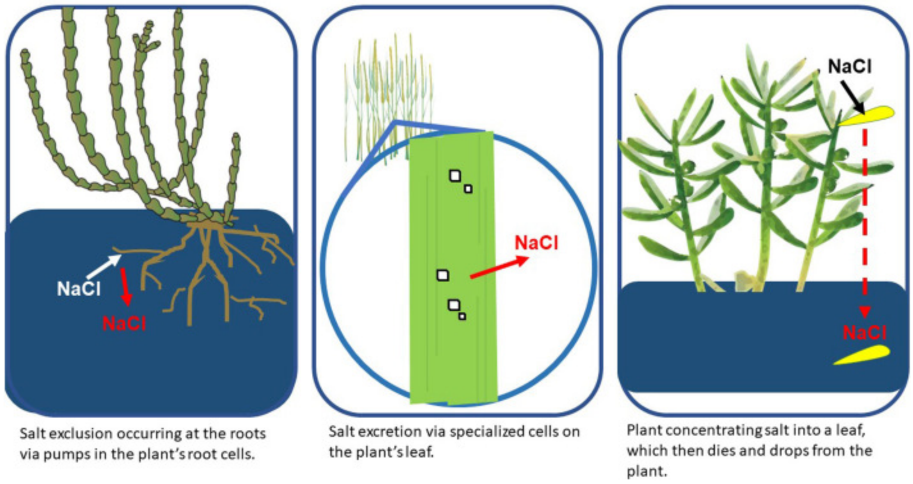

Figure 2

space in one of their leaves and then drop these salty leaves from the plant [6]. These are just some of the many ways that plants living in flooded and salty conditions adapt to survive a stressful life in an estuary (Figure 3).

WHY DO WE NEED TO UNDERSTAND PLANT STRESS?

Knowing what allows plants to live in wetland environments is all very interesting, but why does it matter? First, understanding interactions between species and the places they live increases our knowledge of basic science—the who, what, where, and how of planet Earth. Basic scientific knowledge is always valuable. Furthermore, by understanding how the environment affects various species, we can better understand what is going on when we see changes in the types of plant and animal species living in a particular habitat over time.

For example, sea-level rise, climate change, and other human activities can have big impacts on estuaries, particularly on flooding and salinity. When the physical conditions in the estuary change, plants and animals respond. Scientists can use their knowledge of how species react to stress to better predict how these ecosystems may look and how healthy they will be in the future [7]. Plant communities can thereby serve as an early warning of environmental changes. Responses to change will differ depending on the plant species. For example, if flooding and/or salinity increases in some areas of the estuary, some species may die back or become locally extinct, whereas other species may expand their range. It is important to preserve the plant communities in estuarine wetlands because they provide an important foundation for many other organisms that live in the estuary, like birds, fish, and people.

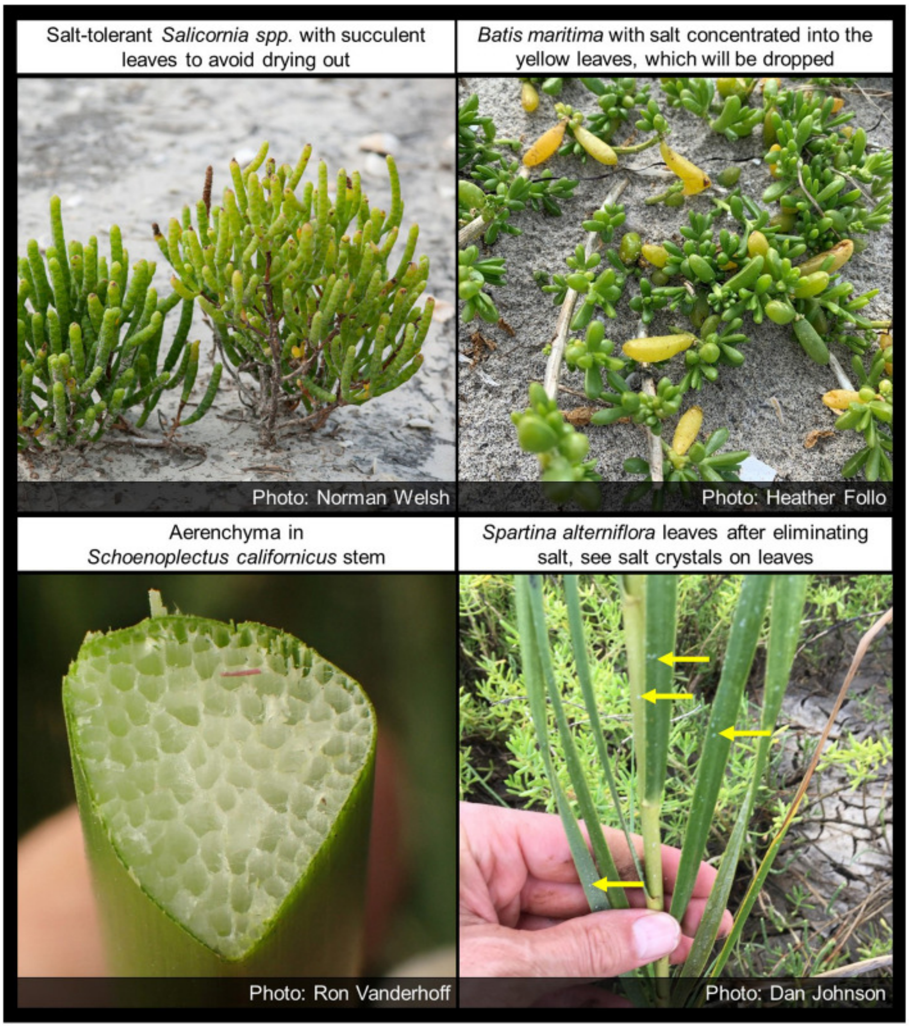

Figure 3

Figure 3

Flood- and salt-tolerant adaptations in wetland plant species that live in the San Francisco Estuary. Top left: *Salicornia* spp. reduce salt stress by having succulent leaves which are thick and contain lots of moisture. Top right: *Batis martima* reduce salt stress by concentrating salt into specific leaves, which then die, and fall off the plant. Bottom left: Some wetland plants, such as *Schoenoplectus californicus*, reduce stress from flooding by forming aerenchyma. The spongy tissue has spaces to enhance air flow in the plant. Bottom right: *Spartina alterniflora* push salt out through special cells in their leaves (Photo credit: BioDiversity4All.org).

Scientists, conservationists, policy makers, and land managers working in estuaries all have an interest in preserving the estuary's biological diversity and ecosystem functions. Understanding plant responses to stressors like flooding and salinity can help land managers maintain the conditions needed to support that biodiversity, as well as alert these professionals to potential problems like ecosystem degradation. If land managers decide to restore parts of the estuary, they must know the physical conditions needed to support the desired plant and animal species. Wetland plant ecologists use knowledge of many plant processes to increase their understanding of wetlands and to help them make decisions for the good of the whole ecosystem.

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YOUNG REVIEWER

KONSTANTIN, AGE: 15

Hi I am Konstantin, your nearby Young Mind! I am from Rousse, Bulgaria and since I was little I had questions like: what is the point in recycling etc. Now, as an adolescent, I really got into ecology and decided to help bring awareness of some of the problems in our world has like the air pollution, species extinction, and deforestation. If I, an ordinary student, can make a difference you can too-so what are you waiting for my young reader!

AUTHOR

TAYLOR M. SLOEY

I am an assistant professor at Old Dominion University in Virginia. I teach classes in plant ecology, marine ecology, and plant physiology. I also lead a research lab that focuses on understanding how wetland plants and ecosystems respond to change. The goal of this type of research is to provide information to help conserve, restore, and manage wetland ecosystems successfully. My favorite part of being an environmental scientist is getting to work outdoors and problem solve with the help of other experts in my field. Learn more about my research at www.taylorsloey.weebly.com. *tsloey@odu.edu

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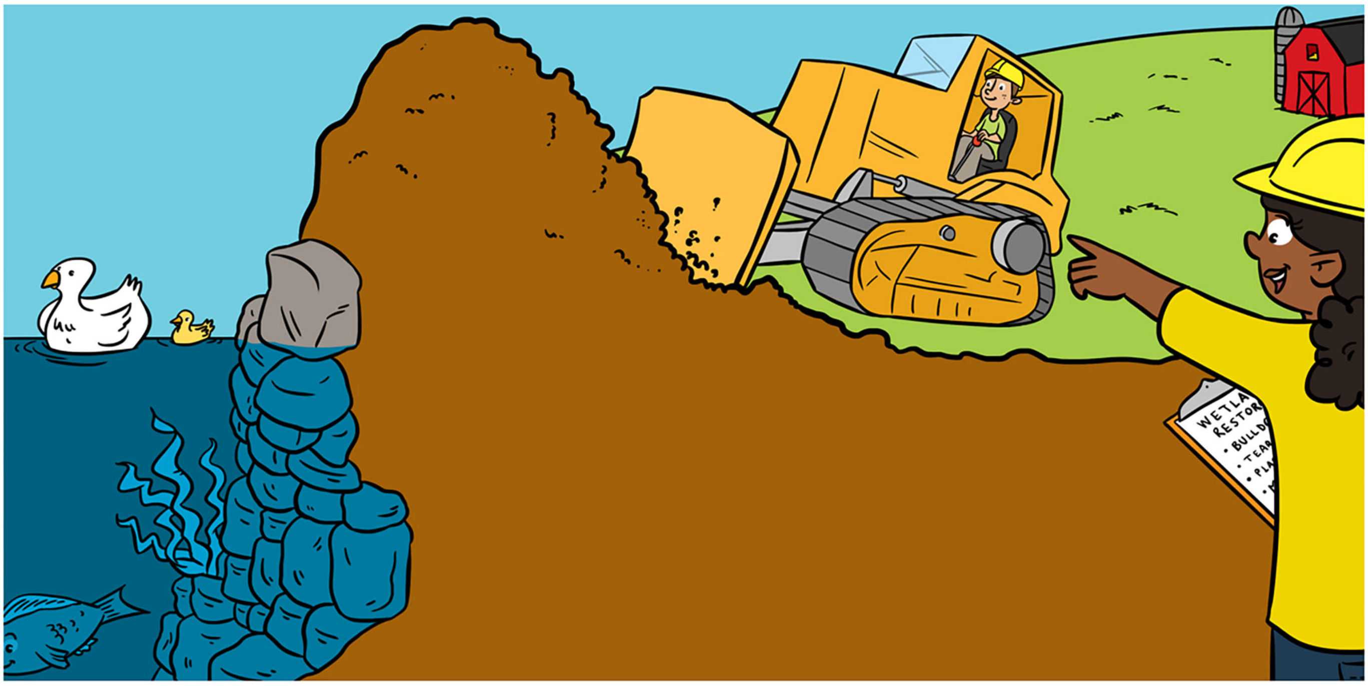

MARSH MADNESS: RESTORING TIDAL WETLANDS IN OUR ESTUARIES

***Stacy Sherman*[1*] *and Rosemary Hartman*[2]**

[1] *California Department of Fish and Wildlife, Stockton, CA, United States*

[2] *California Department of Water Resources, West Sacramento, CA, United States*

YOUNG REVIEWER:

ANUSHA

AGE: 9

Just like people, fish need a safe place to find food and grow up. For fish that travel between fresh water and the ocean, tidal wetlands are a perfect neighborhood, with lots of habitat and food. Tidal wetlands are areas of shallow water where tides from the ocean cover the land with water every day. Besides providing a home for fish and water-loving plants, tidal wetlands also help protect people and their property from natural disasters like storms, and from sea-level rise. People have not always understood the value of wetlands, so billions of acres of them have been filled to farm or build on. In the San Francisco Estuary, more than 90% of wetlands were converted to other uses in <150 years! People now understand why wetlands are important, so protecting and restoring wetlands is a top priority.

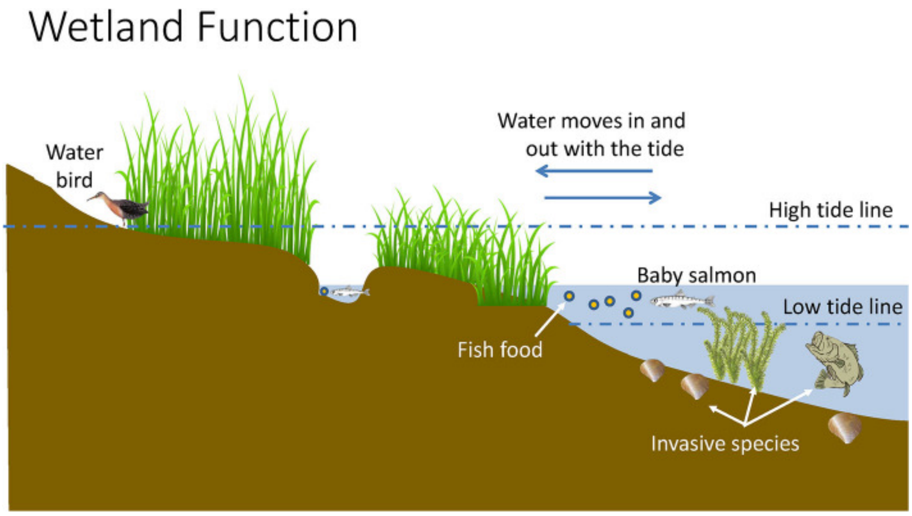

Figure 1

Figure 1

Tidal wetlands are home to water-loving plants and many animals, such as water birds, baby salmon, and the invertebrates they eat. At high tide, the wetland is mostly under water, but at low tide, water is just left in the deeper spots. Water coming out of the wetland with the tide can carry food to fish that do not live in the wetland. Invasive species, such as water weeds, clams, and Largemouth Bass, can also live in or near wetlands.

TIDAL WETLANDS ARE IMPORTANT FOR FISH AND PEOPLE

Just like you, a young fish needs a safe home where it can grow up, and that home needs a fully stocked refrigerator full of tasty, healthy food. Tidal wetlands often are…or were…that home. In estuaries all over the world, including the San Francisco Estuary, large areas of wetlands have been dried out by people so that they can build or farm on the land. Fortunately, we are restoring wetlands to provide a good home for young fish again.

ESTUARY

A partly enclosed area on the coast where freshwater from rivers mixes with salt water from the ocean. Some estuaries have tidal wetlands within them.

TIDAL WETLAND

Land in an estuary or on the coast that is only covered with water when the tide is high. Special plants grow there.

Estuaries? Tidal wetlands? What exactly are these places? **Estuaries** are areas where freshwater from rivers meets the salt water from the oceans. Estuaries can be quite large and include many types of places where animals and plants live. Estuaries can have deep water, shallow water, narrow channels, and big areas of open water. Many estuaries include **Tidal wetlands.** They are shallow areas full of water-loving plants, such as reeds, cattails, and sedges [1]. Water goes into and out of tidal wetlands with the tide, so the land is mostly underwater at high tide, but water is only left in deep spots between the plants at low tide. Many fish depend on tidal wetlands. The plants slow the water down, so that tidal wetlands act like rest areas for fish tired of swimming in fast water. This is especially important for young salmon that are swimming all the way to the ocean from the rivers where they were born. Plants also provide places for young fish to hide from bigger fish that might eat them, and they support lots of invertebrates, including insects and shrimp that fish love to eat. When the tide moves into and out of a tidal wetland, it moves some invertebrates from the wetland to parts of the estuary where the water is deeper [2]. This movement brings food to other fish that do not live in the shallow wetland (Figure 1). Since many humans love to eat fish (especially salmon!), people also benefit from tidal wetlands.

In addition to providing us with fish, tidal wetlands help people in other ways, too. The spongy soils in tidal wetlands act as natural filters, cleaning pollution from the water. Many people get their drinking water from estuaries, so cleaner is better! Tidal wetlands can protect people's coastal houses from floods and storms by absorbing energy and water. The plants that grow in wetlands also take carbon dioxide out of the atmosphere, slowing down climate change [1]. Other animals also benefit from tidal wetlands: otters, snakes, and lots of birds! In fact, the tidal wetlands of the San Francisco Estuary, where we work, are an important part of the Pacific Flyway—the route that many ducks and geese take to travel to and from their winter homes in the south and their summer homes in the north. Birds need to stop and take a rest and have some snacks, too!

MANY TIDAL WETLANDS ARE IN DANGER

People have not always understood why tidal wetlands are so important. Worldwide, wetlands have often been destroyed to make room for farmland or cities [2]. In the San Francisco Estuary, over 90% of wetlands have been lost in the past 150 years (Figure 2). Some of those wetlands were turned into farmland by the building of walls of dirt (called **levees**) to keep the water out. Some wetlands have been converted to duck-hunting clubs, which are still wetlands but are walled off from the rivers, so fish cannot move in and out. Around San Francisco Bay, some former tidal wetlands are used to harvest the salt left behind by evaporating ocean water, and others have been filled in to build neighborhoods and towns. Even the tidal wetlands that still exist are in trouble. These wetlands remove pollution from the water, but pollution can hurt the wetland in the process. Many species from other places have become "invaders," especially in the San Francisco Estuary. The **invasive species** either take over the space (like water weeds), hog all the food (like invasive clams), or even eat the native fish (like the invasive Largemouth Bass) [3, 4]! In the future, sea-level rise caused by global warming may flood the wetlands, making the water too deep for the plants that grow there.

LEVEE

A physical structure, mostly made of dirt, that was built to keep rivers or bays from flooding a piece of land.

INVASIVE SPECIES

Plants or animals from another part of the world that are brought into a new place, get too abundant, and are bad for the species that were already there.

All these problems for tidal wetlands mean problems for fish, too. The numbers of native fish in the San Francisco Estuary have decreased over the past 20 years, and wetland loss may be partially to blame [2]. Many fish in the estuary do not have enough to eat, but scientists find fish with full bellies close to tidal wetlands [3]. Young salmon traveling through the San Francisco Estuary are also in danger of getting eaten by bigger fish. Tidal wetlands provide places to rest and hide. Loss of tidal wetlands could mean the death of more salmon before they reach the ocean.

Figure 2

Most of the tidal wetlands in the San Francisco Estuary have been destroyed or changed to use for other purposes, such as building or farming. Green hatched areas show tidal wetlands in the early 1800s vs. the 2000s.

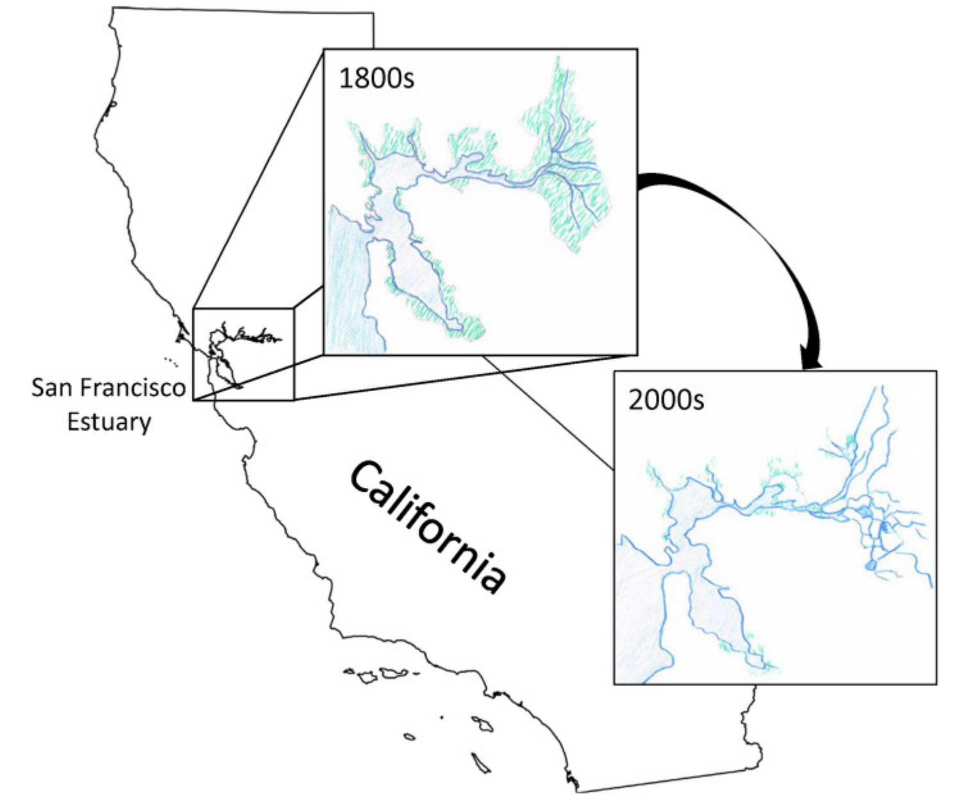

Figure 2

TIDAL WETLAND RESTORATION

RESTORATION

Actions to make an area that was previously changed by humans work in a more natural way to help animals and plants.

Fortunately, people now realize how important tidal wetlands are for both fish and people, so we are starting to restore some of the wetlands we have lost. Tidal wetland **restoration** often involves using bulldozers and heavy machinery to knock down levees and dredge new channels to reconnect dried-out land to the rivers, allowing wetlands to form [1]. Invasive plants are removed and native water-loving plants are added to restore the natural community. Once the plants and the landscape have been restored, fish and invertebrates will find the new wetland and make it their home (Figure 3).

We cannot restore all the wetlands we have lost. In some places, the land is no longer the right depth to be covered and uncovered by the changing tides, so native aquatic plants will not grow there [1]. Also, restoring wetlands is expensive, and restoration can sometimes harm other species that live in the area [4]. Moving enough dirt to restore the natural ecosystem is a lot of work and disturbs all the plants and animals living in the area during the construction!

Because tidal wetland restoration is such a big investment, we want to be sure restored wetlands provide a good home for fish and other wildlife. Therefore, after restoration, we take measurements of plants, invertebrates, fish, water quality, and landscape change for many years, to make sure the restored area is working the same as the original

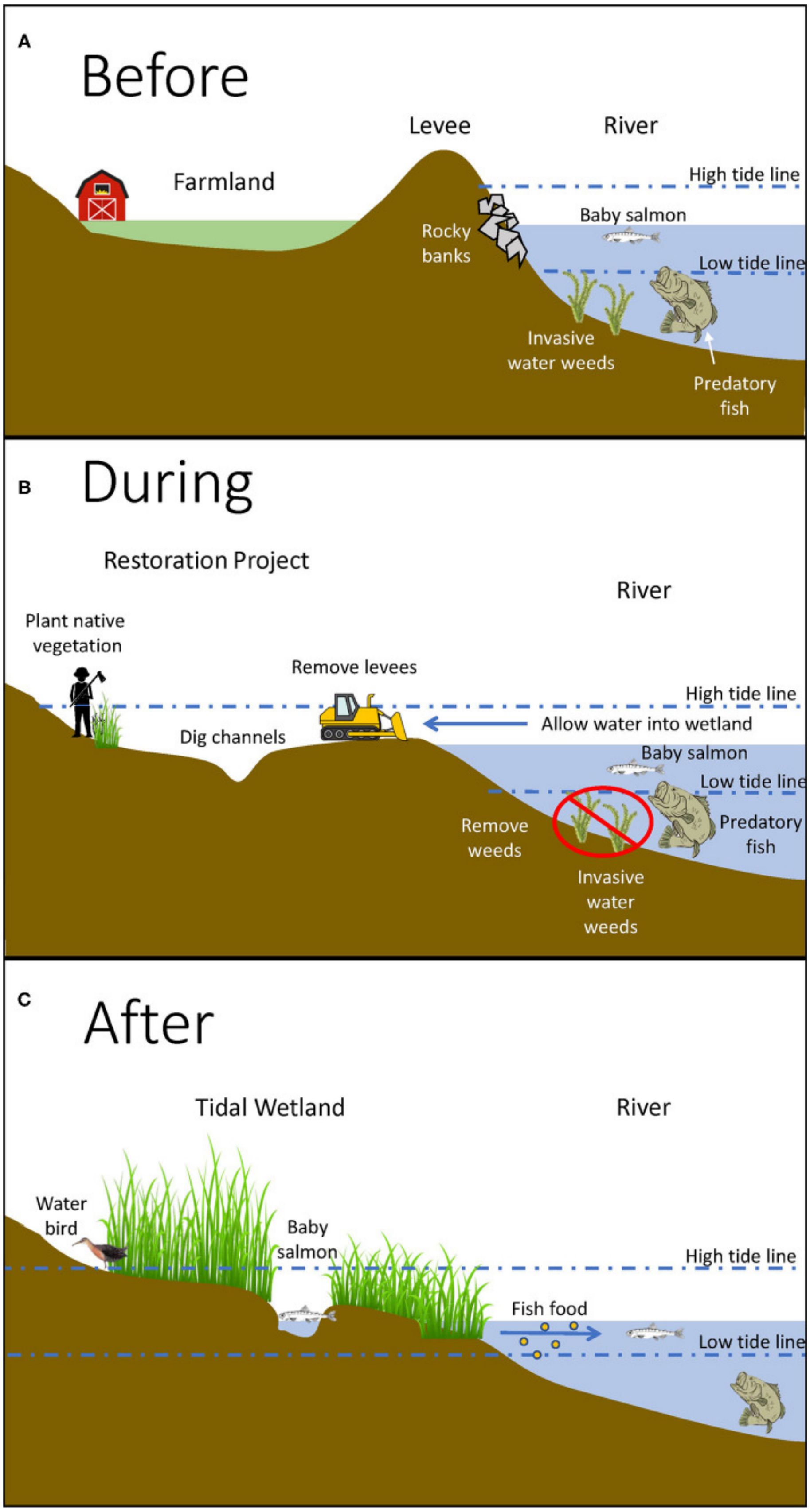

Figure 3

Figure 3

(A) Before restoration, dry land is separated from tidal waters by structures like levees. **(B)** Construction is performed to remove levees and invasive plants, and native plants may be added. **(C)** Restoration can create a functioning tidal wetland, in which native species can thrive.

wetland. If the tides cannot come in and out properly, if the native plants won't grow, if there are few invertebrates present, or if the fish do not find it, we know we did not restore the wetland properly. In that case, we might make additional changes, such as putting in new channels, filling in other channels, taking out more invasive plants, or putting in new plants. We use our scientific monitoring to guide these changes and we also learn from our experiences, so that we can make future restoration better—that's what we call **adaptive management** [4].

ADAPTIVE MANAGEMENT

Taking an action (like restoration), watching to see what works (or does not work), and learning to make future actions better.

We have already seen evidence that restoration helps fish, both in the San Francisco Estuary and in other, similar estuaries. Tidal wetland restoration in Puget Sound (Washington State) has made homes for lots of young salmon, and they are now bigger and healthier when they reach the ocean than they were before restoration [5]. Some fish that look for food near tidal wetlands in the San Francisco Estuary find more invertebrates than do fish that try to find food in river channels [3]. It's like the wetlands are a series of rest-stops, with restaurants and motels for the traveling fish!

WHAT CAN YOU DO TO HELP PROTECT WETLANDS?

There are some simple things that you can do every day to help protect wetlands and their benefits for fish and people!

First, be an Earth Hero! Take care of the environment right where you are. Believe it or not, substances like chemicals, plastics, and even soapy water that get into storm drains can pollute the waterways that lead to wetlands. If you have an aquarium, never release the animals or plants into the wild—they might just end up as the next invasive species!

Now that you know how important tidal wetlands are, you can also get to know and love a wetland near you! If you live near or visit the San Francisco Estuary, the Yolo Bypass Wildlife Area, Elkhorn Slough Wildlife Area, and Rush Ranch are just a few of the places where people can safely get up close and personal with wetlands. If you do not live near a tidal wetland, you can still experience how beautiful and full of life they are by visiting websites that describe these areas[1] . You can also help to celebrate wetlands everywhere on World Wetlands Day, February 2 each year[2] !

Finally, keep learning about tidal wetlands and tell your friends and family about what you have learned. We need more people to understand and appreciate these important areas. Who knows, someday you might even become the next great wetlands scientist!

[1] https://www.yolobasin.org/virtualwetlandtours/, https://www.elkhornslough.org/story/, https://oceanconservancy.org/blog/2020/05/14/experience-americas-wetlands-home/

[2] Worldwetlandsday.org

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YOUNG REVIEWER

ANUSHA, AGE: 9
I am a 9-year-old girl and I am in 3rd grade. I love to read books, especially fantasy and science-fiction. I have finished reading the Harry Potter, Percy Jackson, Magic Tree House, The Time Machine, and The Lord of The Rings series. I want to be part of this review process because I want to continue to learn and help other kids to learn by volunteering as reviewer.

AUTHORS

STACY SHERMAN
My team at the California Department of Fish and Wildlife studies how restored tidal wetlands in the San Francisco Estuary benefit native fish. We provide data to help people improve future restoration projects. As a Cajun, I grew up in Louisiana, among wetlands, on the water, and eating amazing seafood. I feel very lucky to have a career learning about and protecting special ecosystems. Outside of work I enjoy building/sewing/painting things, riding my bike, and spending time with my family, which includes two cute and goofy rescue mutts: Hazel and Lucy. *stacy.sherman@wildlife.ca.gov

ROSEMARY HARTMAN
My job involves taking information from all the monitoring programs around the region and using it to answer big questions, like "How can we save native fish?" I work on many different topics, but wetlands are special to me because I used to be on the monitoring team for wetland restoration in the Delta. I have worked in wetlands all over the country—including the Everglades, the marshes of Wisconsin, the mountain meadows of the Rockies, and the mangrove swamps of the Florida panhandle. In my spare time, I love hiking, biking, birding, and exploring the outdoors of California.

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HELPING NATURE IN THE SAN FRANCISCO ESTUARY COPE WITH CLIMATE CHANGE

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Delta Stewardship Council, Sacramento, CA, United States

YOUNG REVIEWERS

EUROPEAN SCHOOL OF VARESE

AGES: 12–13

Estuaries are special places that form where freshwater from the land mixes with saltwater from the ocean, which is pushed inland by the tides. This mixing creates diverse habitats that support a variety of specially adapted species. In estuaries with Mediterranean climates (similar to that of the Mediterranean region in Europe), winters are wet and summers are dry. Some winters have lots of rain, others have almost none. The animals and plants of California's San Francisco Estuary have adapted to these variable conditions. But humans have changed how and when the water flows through the Estuary, making it tough for some species to survive. Climate change is likely to bring hotter air and water temperatures, more extreme floods and droughts, and rising sea levels, further complicating species survival. In this article, we discuss how ecosystem restoration and water management can help species survive in a changing climate.

Figure 1

The San Francisco Estuary. The waterways are in blue, the area of the inland delta is in green. The Sacramento River in the north and the San Joaquin River in the south meet in the Delta, then flow through Suisun, San Pablo, and San Francisco Bays into the Pacific Ocean. Sacramento, the capital of California, is located on the Sacramento River. The water-pumping plants pump water from the Estuary all the way to southern California.

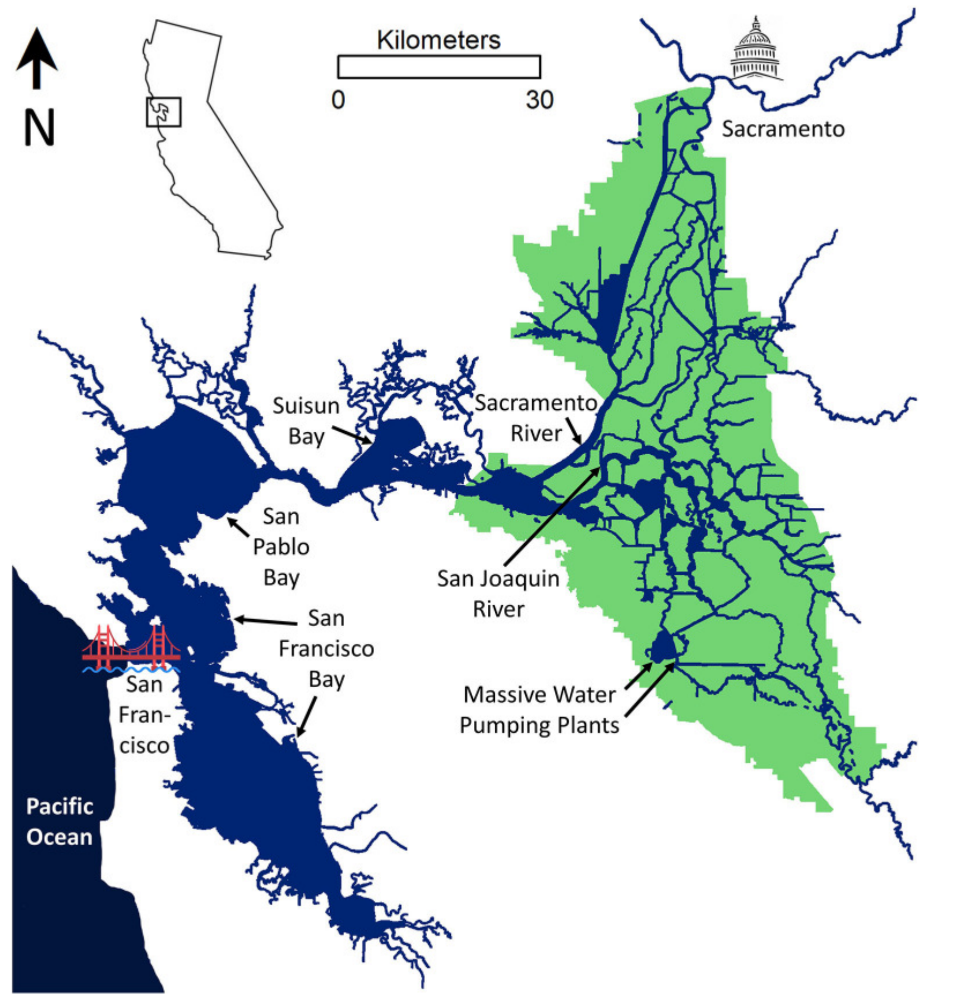

Figure 1

THE SAN FRANCISCO ESTUARY

What do people who live in Los Angeles, the almonds in your trail mix, and salmon have in common? They all depend on water from the San Francisco Estuary! **Estuaries** form where rivers meet the ocean. The San Francisco Estuary is located near the city of San Francisco in northern California, USA (Figure 1). It is a special estuary, in part because much of its water is pumped out and transported over hundreds of kilometers in concrete channels, to provide water to over 25 million Californians and over 12,000 km^2 of agricultural crops. Another thing that makes the San Francisco Estuary special is its wild and crazy climate. In the summer, it does not rain for months on end, but winters are wet. Well, some winters. During **drought** years, it may not rain at all. And during very wet winters, large areas of the Estuary can flood. There is no such thing as a "normal" year for the San Francisco Estuary [1]. However, this climate variability *is* normal for places like California, which has a Mediterranean climate—like that of the area surrounding the Mediterranean Sea in Europe.

ESTUARY

A coastal area, enclosed by land, where fresh river water mixes with salt water from the ocean.

DROUGHT

A period of time when a place gets less than normal precipitation (rain or snow).

ADAPTATIONS TO A CRAZY CLIMATE

Plants and animals that live in estuaries located in Mediterranean climates are well-adapted to both raging floods and long droughts. They have developed various physical and behavioral mechanisms to help them survive all the different, crazy weather events. Wetlands are critical habitats for many fish and bird species [2] and, in the San Francisco Estuary, over 80% of the wetland species have been lost since the 1800s [3]. Wetland plants have developed certain adaptations to tolerate the changes in **salinity** that accompany both floods and droughts [4]. Migratory bird species evolved to follow the water, taking advantage of **seasonal habitat** across the region [5]. These adaptations have allowed species to shift and change over time, in response to climate conditions. You can read more about the strategies of a specially adapted fish species in Fichman et al. [6].

SALINITY

Varies with the amount of mineral salt dissolved in water. Oceans have high salinity due to high salt content, rivers have low salinity, due to low salt content.

SEASONAL HABITAT

Habitat used by a migrating species for only specified season(s) of the year.

AN ALTERED LANDSCAPE

You might think that the unique species of the San Francisco Estuary would be prepared for climate change—after all, they are adapted to survive crazy weather! And that might be true if it was not for one other "little" issue. In many estuaries, including the San Francisco Estuary, important habitats such as wetlands, stream channels, and **floodplains** have been turned into agricultural fields, cities, and towns. People have changed the Estuary by filling in some channels, deepening and straightening others, and building **levees** to keep fields and houses from flooding (Figure 2). In addition, lots of water that would naturally flow through the San Francisco Estuary to the ocean is being diverted from the Estuary for humans to drink and for watering crops. These changes have destroyed most fish and wildlife habitats and have greatly altered water flow patterns, making it harder for **native species** to cope with climate change [1, 7].

FLOODPLAIN

An area of low-lying ground adjacent to a river, formed mainly of river sediments and subject to flooding.

LEVEE

A wall that prevents water from going where we do not want it to go. Also called a dike or embankment. It can be either naturally or artificially constructed.

HOW DOES CLIMATE CHANGE AFFECT THE SAN FRANCISCO ESTUARY?

Climate change threatens the San Francisco Estuary in a variety of ways.

NATIVE SPECIES

Plants and animals that occur naturally in a particular region without human introduction.

Sea Level Rise

Sea level rise is caused by ocean water expanding as it gets warmer and ice sheets on land melting. The direct connection between the San Francisco Estuary and the ocean means that extreme sea level rise can permanently drown wetlands, which are a key habitat for many plants and animals. In the past, wetlands could move inland to higher elevations as tides got higher. But today, levees, roads, and cities prevent wetlands from shifting inland. Models predict that some wetlands may survive sea level rise, but others will probably drown over

Figure 2

Figure 2

The San Francisco Estuary today. People built levees on the sides of the rivers and channels to protect their farms and homes. There are few small channels or marshes for fish and wildlife to live in (Photograph credit: California Department of Water Resources).

time, which is particularly problematic because most wetlands have already been lost [4].

Levee Failure

A rising sea level combined with extreme floods may cause levees to fail. Levee failure would flood the areas that are behind the levees and now below sea level. To read more about levees and the risk of island flooding, please see Stern et al. [8]. Although this flooding would be disastrous in many ways, it may create more habitat for some aquatic plants and animals [1].

Rising Water Temperatures

Another threat comes from rising water temperatures. In the San Francisco Estuary, spring and summer water temperatures are likely to increase by 1–5.5°C (1.8–9.9°F) over the next few decades. This will be stressful for native species that are adapted to lower temperatures and will likely change the timing of important life events, such as reproduction. Lacking the many microhabitats that are common in a natural estuary, including deeper waters, water shaded by cottonwood or willow trees, fast-flowing water, and groundwater-fed cooler pools, native species will have a harder time persisting [7].

Higher water temperatures also affect salmon. For thousands of years, these amazing fish have laid their eggs in small, cold streams upstream from the Estuary. Their babies hatch in streams and then migrate through the Estuary to the ocean, where they stay until they are grown and ready to return to their birth streams to lay their own eggs. Because dams block access to the clear mountain streams in which salmon used to reproduce, they now lay their eggs at much lower, warmer elevations, but still return to their birthplace to reproduce [9]. If droughts become more frequent and water temperatures keep rising, salmon may disappear from this region, because of a lack of cool water that salmon eggs and young need to grow. People who operate dams can use cold water from the reservoirs to keep the streams below cold when the salmon need it for reproduction, but in years with little rain to fill the reservoirs, this is not an option [1].

Droughts

Droughts cause warmer water temperatures and keep seasonal floodplains dry. Extended droughts are hard on native fishes, because some fish are sensitive to warm water temperatures and many use floodplains for spawning and for feeding. Floodplains only fill with water in rainy winters, or when a lot of snow melts in the mountains [1]. Before levee construction, floodplains were common along the streams in the upper Estuary. Wet floodplains produce lots of fish food, provide habitat for young native fish, and shelter those young fish from predators [1].

Salty or Fresh Water

In estuaries, the salinity of the water increases the closer you get to the ocean. Water salinity in certain locations changes throughout the month, the year, and between years. High tides push the salty water further up into the Estuary; melting snow in the mountains brings fresh water down the rivers and makes the Estuary less salty. In dry years, the salty water can travel further into the Estuary than in wet years. Animals and plants living in estuaries are used to these changing conditions and can handle them if habitat is available along the whole stretch of the Estuary [1].

Because water from the San Francisco Estuary is pumped out for drinking water and for watering almonds, fruits, and vegetables, water managers keep the salty water from coming far up the Estuary. They catch water in upstream reservoirs in the wet season and release this water in the dry season. These management actions result in less salty but also less variable conditions, which are better for non-native or **invasive species** that are not adapted to the normal, varying conditions and can outcompete the native species [1]. To read more about the effect of invasive species see Morais et al. [10].

INVASIVE SPECIES

Species not originally from an area; "non-native," which when introduced displace and make habitats unsuitable for native species.

WHAT CAN WE DO?

Each species responds in its own unique way to changes brought about by climate change. While we expect the effects of climate change on an estuary to be profound, predicting exactly how species and ecosystems will respond is nearly impossible.

Figure 3

A vision of the San Francisco Estuary in which nature-filled landscapes surround the rivers, offering space for fish and wildlife to thrive and for people to enjoy (Image credit: Yiping Lu, San Francisco Estuary Institute).

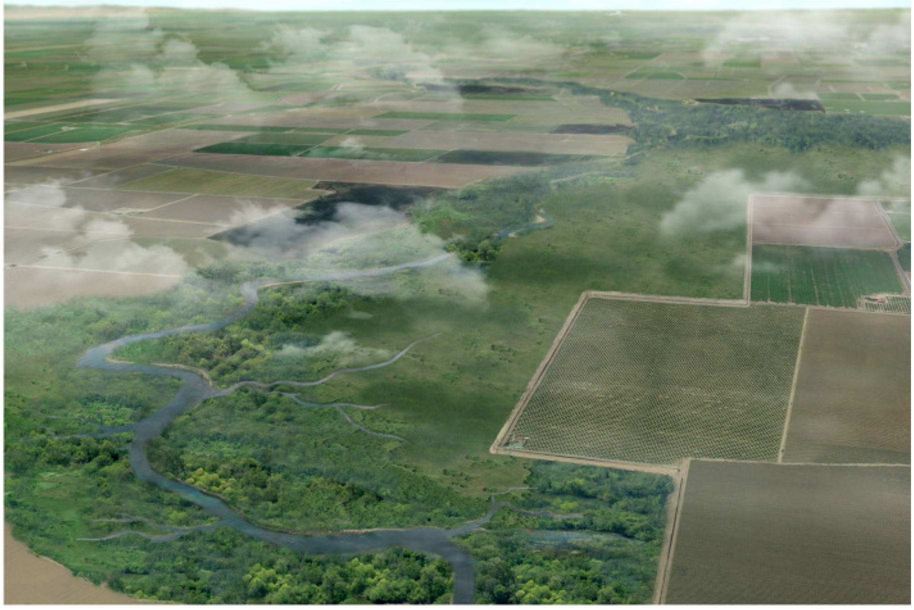

Figure 3

There are three approaches to making an estuary more resilient to climate change. First, we must continue monitoring and researching fish and wildlife, salinity, water temperature, and other factors. The more we know about how the ecosystem works and responds to changes, the more effectively we can manage it. Second, it is important to restore the different ecosystems of the Estuary, particularly wetlands and floodplains, to create more habitat. A large amount of intact natural areas will offer a diversity of microhabitats, allowing fish and wildlife to move to where conditions are best for their survival (Figure 3). Finally, we should try to manage the water flowing through the Estuary, to create suitable and varying conditions for native animals and plants. In the San Francisco Estuary, this may present the greatest challenge because of the importance of the Estuary for providing water for humans.

Scientists are sure that human activity is responsible for the climate change we see today; the good news is that it means we can do something about it. In the Estuary and around the world, people are working together to understand and address the impacts of climate change. Articles like this one explaining the science of climate change can help us identify what solutions are available and move them forward.

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YOUNG REVIEWERS

EUROPEAN SCHOOL OF VARESE, AGES: 12–13

This group of international and hungry minds took the opportunity to engage in this new scientific activity and managed to make the difference by working wonderfully together!

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