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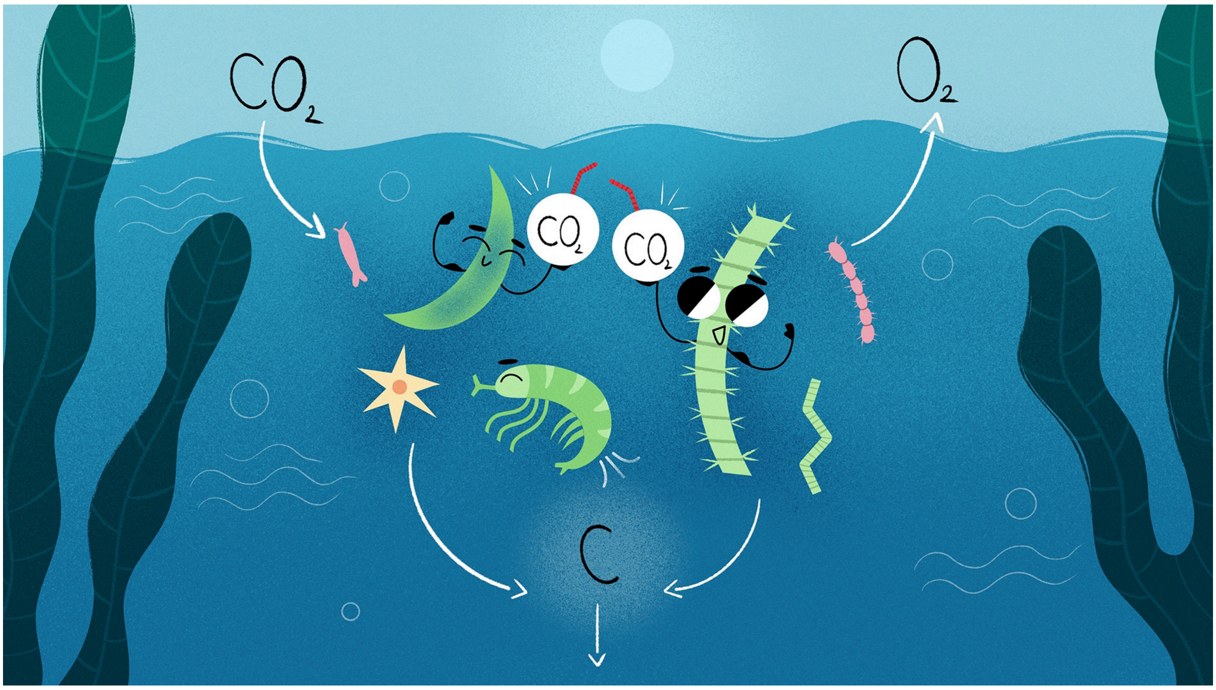

FRESHWATER ECOSYSTEMS: CARBON SEQUESTRATION CHAMPIONS

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Nature helps us fight climate change by removing carbon from the atmosphere and storing it underground—a process called carbon sequestration. Some freshwater ecosystems, like lakes, are great at carbon sequestration. Surprisingly, small organisms play a big role here! When tiny algae and bacteria in the water photosynthesize, they take carbon dioxide from the atmosphere and convert it to organic carbon (the carbon that forms all living organisms). The organic carbon moves through the ecosystem as it is eaten by other organisms or as it sinks to the bottom as either poop or the remains of dead organisms. When organic carbon reaches the bottom, it can remain buried for a long time. Aquatic plants and material from land that washes into freshwater can also sink and end up as sequestered carbon. It seems like freshwater ecosystems sequester carbon more efficiently than other environments, but scientists still

have more work to do. Because of the huge diversity of water bodies across the world, scientists need to know which are the real carbon sequestration champions.

CLIMATE CHANGE AND FRESHWATER ECOSYSTEMS

Nature helps us fight climate change by removing carbon from the atmosphere and storing it underground—a process called **carbon sequestration**. Carbon sequestration happens in ecosystems all around the world. Forests and oceans are most well-known for sequestering carbon, but freshwater ecosystems like **wetlands** and lakes are also great at it (Figure 1). To put this in perspective: freshwater ecosystems might sequester up to 20% of the amount of carbon sequestered by the oceans, even though they cover <5.6% of the area that oceans cover (Figure 1A). Some wetlands in tropical areas are true carbon champions—they sequester more carbon per square meter than any other ecosystem! But what processes drive carbon sequestration in inland waters, and why are these ecosystems so efficient at it? In this article, we will answer these questions.

CARBON SEQUESTRATION

The process of capturing and storing carbon dioxide from the atmosphere in organic materials that get buried in sediments for long periods of time.

WETLANDS

Areas where the land does not drain well, and the ground is full of water like marshes or swamps.

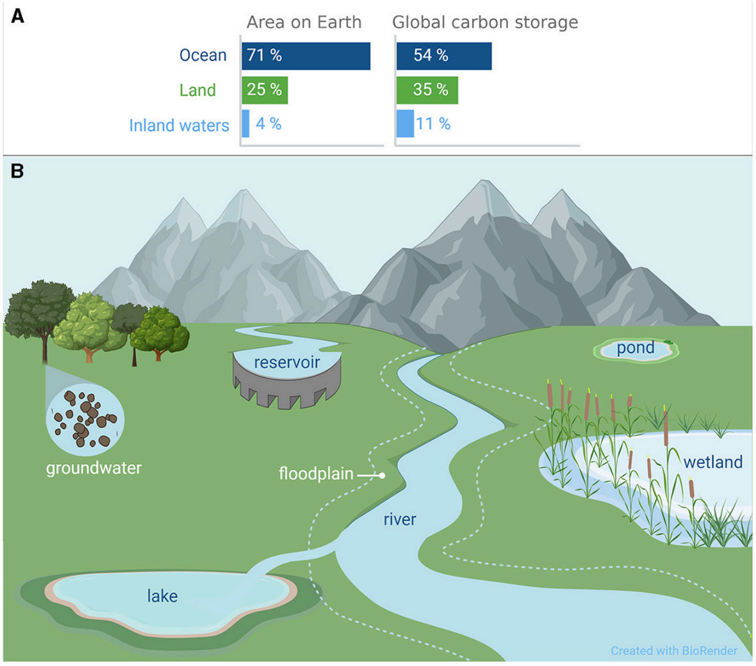

Figure 1

Figure 1

(A) Percentage of Earth's area and carbon storage ability of oceans, land, and inland waters. This graph shows that freshwater ecosystems are good at storing carbon, even though they take up much less area than the oceans. **(B)** There are multiple types of freshwater ecosystems on Earth. Non-flowing or slowly flowing freshwater ecosystems (lakes, ponds, reservoirs and wetlands) are best at carbon sequestration.

To understand carbon sequestration, you must first know something about freshwater ecosystems. Freshwater ecosystems include flowing waters, like rivers and streams, and non-flowing waters, like lakes, **reservoirs**, ponds, and wetlands (Figure 1B). Freshwater ecosystems come in many shapes and sizes: from a small layer of water in a ditch, to the 1,600-meter-deep Lake Baikal in Russia. The organisms that live in freshwater ecosystems also come in all sizes,

RESERVOIR

Manufactured lakes that have been built to store water.

like bacteria, insect larvae, fish, underwater plants, and amphibians. Most carbon sequestration happens in non-flowing or slowly flowing aquatic ecosystems.

CARBON CYCLE IN THE AQUATIC FOOD WEB

As we mentioned, many kinds of organisms live in freshwater ecosystems (Figure 2). Living organisms can be categorized into two main types: primary producers and consumers. Primary producers can make their own "food" through photosynthesis. Primary producers use **inorganic carbon**, in the form of carbon dioxide (CO_2), to produce **organic carbon**, like carbohydrates and proteins. Organic carbon is used for food and growth and becomes part of the primary producers' cells. Consumers, on the other hand, are organisms that need to eat the organic carbon that builds primary producers, to build their own new cells and grow. Both primary producers and consumers are linked together through the food web, which describes who eats whom in the environment.

INORGANIC CARBON

The carbon found in non-living things, like rocks, water, and air.

ORGANIC CARBON

The carbon found in living things or their remains, like plants and animals.

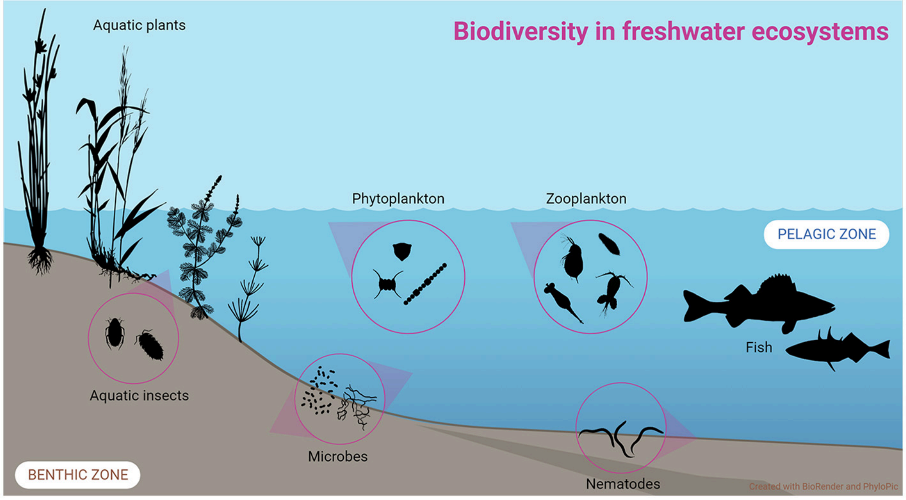

Figure 2

A wide variety of organisms live in both the pelagic (open water) and benthic (bottom) zones of freshwater ecosystems. Pink circles zoom in on microscopic organisms, with lengths ranging from 0.0002 mm (bacteria) to 4 mm (zooplankton).

Two types of food webs in freshwater are crucial for carbon sequestration. The first is the planktonic food web, which includes organisms in the open water (**pelagic** environment). The second is the **benthic** food web, which includes organisms at the bottom, close to the sediments (Figure 2).

PELAGIC

The open water between the water surface and the benthic zone.

BENTHIC

The area at the bottom of the water, where the sediment and the water meet.

In the open water, which organisms are important for carbon cycling? You might be thinking of fish and bugs, but the microscopic organisms in the planktonic food web are the heroes of carbon cycling. Plankton is a group of microscopic organisms that float, drift, or swim weakly through the water. Most species of freshwater plankton cannot be seen by the naked eye: the largest are only a few millimeters long, while the smallest are less than a thousandth of this size. Phytoplankton are a type of plankton made up of microscopic algae and bacteria. They are the primary producers. Zooplankton, made up of various tiny animals, are the consumers that feed on phytoplankton. In turn, zooplankton are eaten by animals higher in the food web—like larger zooplankton, aquatic insects, or small fish, which are in turn consumed by larger fish. In this way, carbon flows from primary producers at the bottom of the food web to predators at the top.

At the bottom of the water body, organisms live on or close to the sediments and make up the benthic food web. The primary producers in these ecosystems include aquatic plants and benthic algae that live on the surface of plants and sediments. Consumers include leeches and snails, insect larvae, crustaceans, and fish. The pelagic and benthic food webs are interconnected, and carbon flows between them until it is either sequestered in the bottom or returned to the atmosphere as CO_2.

CARBON SEQUESTRATION: REMOVAL OF CO_2 FROM THE ATMOSPHERE

How do plankton contribute to carbon sequestration? By producing sinking particles full of organic carbon. When plankton die, their remains can rapidly sink to the bottom. Also, while alive, zooplankton produce fast-sinking poop full of organic carbon from the phytoplankton they eat. Plankton remains and poop sink and transport organic carbon, but not all carbon makes it to the bottom. During the descent, these particles are rapidly attacked by microbes like bacteria and fungi that break them down [1]. In the decomposition process, the microbes produce CO_2, which eventually returns to the atmosphere. However, if dead plankton and poop escape microbial decomposition and reach the bottom, they (and all the carbon they contain) can be buried (Figure 3). When carbon stays deep underground, it is stored there and kept out of the atmosphere. And that is what we need to help fight climate change!

What happens in the benthic zone? Aquatic plants increase carbon sequestration because they trap sediments produced in the waterbodies or transported into the water from land. These sediments contain organic carbon, which is then deposited at the bottom. Aquatic plants also take up a lot of CO_2 to grow. They are often large and rich in organic carbon that makes it difficult for microbes to break down. Thus, lots of organic carbon sinks into the sediments when aquatic plants die.

Another source contributes to carbon sequestration in inland waters—organic carbon transported from land. Through rivers and runoff, water and other materials like soil and land plants are transported to freshwater ecosystems. This material is likely to quickly sink to the bottom where it is buried and the carbon is sequestered,

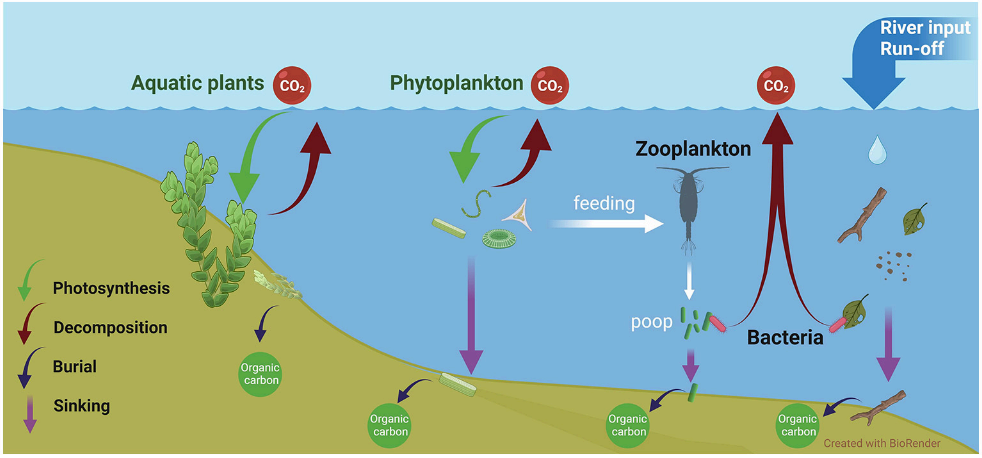

Figure 3

Figure 3

Carbon movement through a lake ecosystem. CO$_2$ from the atmosphere is converted to organic carbon by phytoplankton and aquatic plants during photosynthesis. Then, the carbon can be transferred up the food web as consumers eat the primary producers, or it can be exported to the bottom in the form of dead organisms or poop. Carbon from land can also enter the lake through rivers and sink to the bottom. If the carbon is not decomposed and reaches the bottom, it can be sequestered from the atmosphere.

because it is difficult for microbes to decompose, especially in the low-oxygen conditions found on the bottom of waterbodies like wetlands and some lakes.

DO FRESHWATER ECOSYSTEMS HELP FIGHT CLIMATE CHANGE?

Carbon sequestration rates in inland waters have increased in the last decades due to human influences on the environment [2]. This happens because of three main reasons. First, when forests are cut down, the soils erode and rivers carry more material from land that can be stored in lakes. Second, humans use fertilizers in farming, which can reach freshwater ecosystems and cause a lot of phytoplankton growth. This leads to more organic carbon production and export to the bottom. Third, building dams in rivers creates artificial lakes that trap and bury sediments and carbon. These three things seem to tell us that freshwater ecosystems might help to fight climate change by storing more carbon, but are we sure of that?

For a long time, inland waters were seen as unimportant to the carbon cycle because they cover <4% of the Earth. But now scientists know that freshwater ecosystems can be important for carbon sequestration [3]. We know that carbon sequestration is a balance between carbon uptake during photosynthesis, carbon breakdown by microbes, and carbon burial at the bottom of inland waters. When the decomposition is too high, inland waters become a source of greenhouse gases and release CO$_2$ or methane (CH$_4$) into the atmosphere. In that case, they do not help to fight climate change because these gases contribute to global warming. However, when the photosynthesis and burial of carbon are higher than its breakdown, inland waters do contribute to fighting climate change.

Nowadays, the balance between photosynthesis, decomposition, and burial is changing due to climate and environmental changes. For example, large wetlands that were frozen for millennia are thawing and decomposing around the Arctic. Human changes to the environment increase carbon burial and storage, but they can also speed up the rates of greenhouse gas production. Therefore, researchers are trying to understand whether carbon emissions as greenhouse gases and carbon burial will balance each other out as freshwater ecosystems change. With more studies in changing environments and areas that have not been studied yet, scientists can make a better estimate of the carbon sequestration rates in freshwater ecosystems all over the world. Nevertheless, the evidence we have so far shows that inland waters play an important role in carbon sequestration, and they may help to fight climate change.

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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

ANTONIO, AGE: 11

Antonio is a big fan of science—especially anything involving plants or birds. Equally important is, of course, soccer! In his spare time, Antonio enjoys playing chess, drawing cool pictures of birds, and watching Naruto.

CALEB, AGE: 11

Caleb enjoys all things science, animals, reading, exploring the outdoors, playing the violin, and curling. When he grows up, Caleb wants to be an architect focusing on eco-friendly and animal-oriented buildings. He has tried four sports and is always up for trying something new. Caleb's favorite foods are macaroni and cheese or lasagna. He enjoys traveling and would like to go to an animal reserve.

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I am a marine biologist from Chile. My research aims to understand plankton's role in carbon and nitrogen cycling via the production of sinking particles and their interaction with microorganisms. I study both marine and freshwater ecosystems. At the Netherlands Institute of Ecology, I work as a postdoctoral researcher investigating how phytoplankton affect carbon sequestration in shallow lakes. In my free time, I enjoy practicing kung fu and yoga. *belen.franco.c@gmail.com

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I am a Ph.D. candidate in the Netherlands at the Netherlands Institute of Ecology and the University of Amsterdam. I try to answer questions about phytoplankton like when do cyanobacterial blooms become toxic, or how do algae interact with plastics? In my free time, I enjoy going for a bike ride, playing the piano, and reading a book in my hammock.

VERA VAN SANTVOORT

I am a Ph.D. student in the department Aquatic Ecology of the Netherlands Institute of Ecology (NIOO-KNAW). I have always had a broad interest in biodiversity, ecology, and nature conservation. Therefore, I like working at NIOO-KNAW: an institute at the forefront of ecological research, promoting biodiversity. My research focusses on rapid evolution in zooplankton. We are investigating whether rapid evolutionary adaptation can help zooplankton deal with stress caused by increased levels of salt in freshwater ecosystems. This is important because of climate change: to what extent are organisms and ecosystems able to deal with increased stress levels?

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I am a Ph.D. student in the Aquatic Ecology Department of the Netherlands Institute of Ecology. Through my research, I aim to understand how global change impacts toxic cyanobacteria on the cellular level, and how this scales onto the ecosystem level. When I am not working, you can find me outdoors, in the mountains, or underwater exploring.

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I am a palaeolimnologist and freshwater ecologist, interested in looking at lake processes across different timescales. I am Head of the Aquatic Ecology group at the Netherlands Institute of Ecology, and previously worked in the UK, Canada, Malaysia, and Denmark, across a wide range of freshwater ecosystems. In my free time, I enjoy long-distance train trips and cycling around Gelderland sampling the excellent beers.