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Edited by
Jc Burgelman and Idan Segev

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Frontiers Planet Prize 2024, Volume 2

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Earth Sciences

Human Health

Biodiversity

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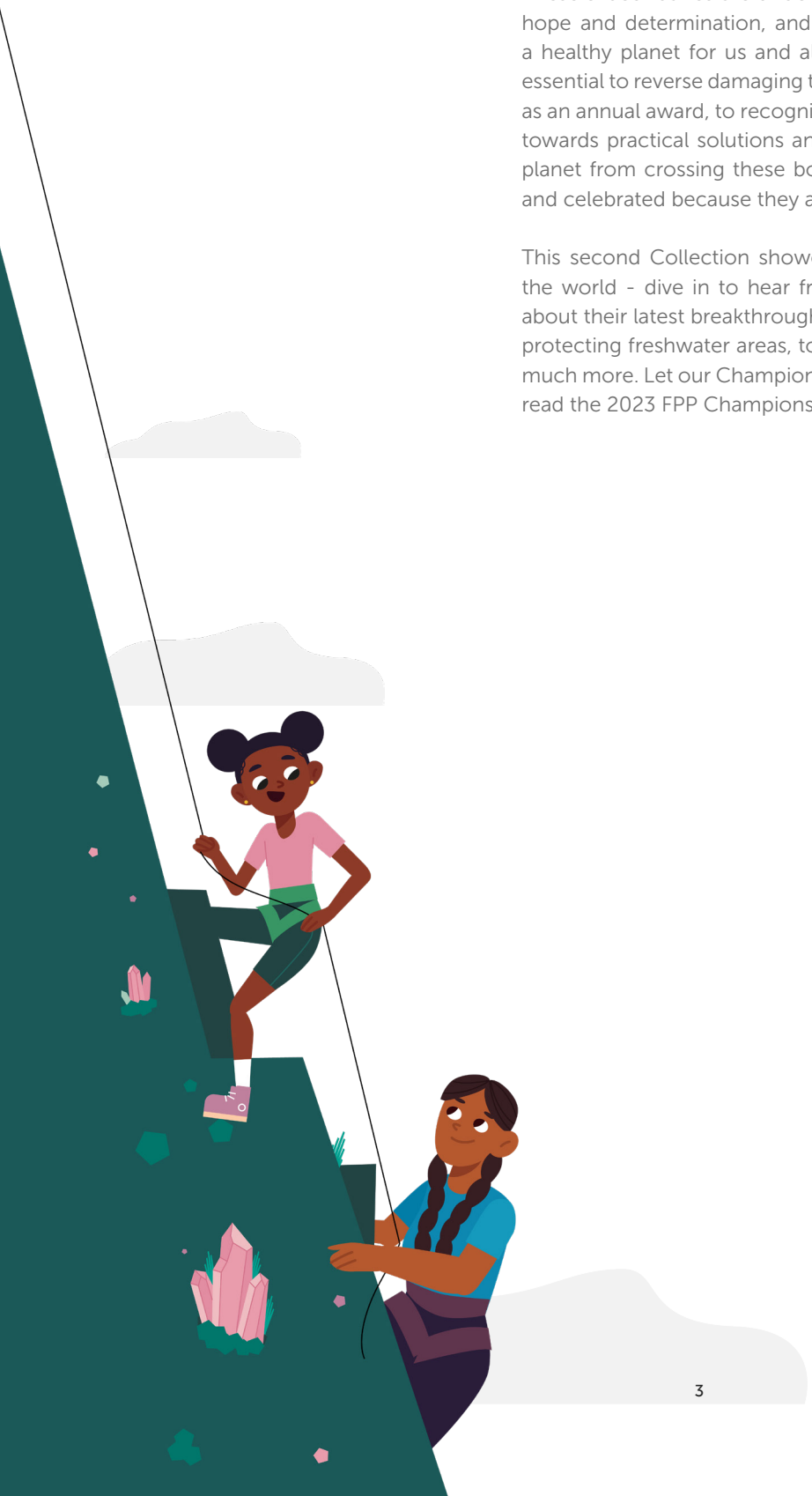
About this collection

Planet Earth has a natural ecological balance, within which we can continue to live healthy lives, but human activities pose a critical threat to this. There are nine crucial areas for keeping this balance stable, called the nine planetary boundaries - mapped by international scientists and described by Professor Professor Johan Rockström and Owen Gaffney in their book Breaking Boundaries.

These 9 boundaries are under serious threat, so we must join together, with hope and determination, and take action now to preserve healthy lives on a healthy planet for us and all species. Science - all areas of science - are essential to reverse damaging trends, so the Frontiers Planet Prize was created, as an annual award, to recognise scientists around the world who are working towards practical solutions and technological breakthroughs to prevent our planet from crossing these boundaries. Planet Prize Champions are chosen and celebrated because they are mobilizing action at scale.

This second Collection showcases the 2024 FPP Champions from all over the world - dive in to hear from these top researchers in their own words about their latest breakthrough work, from the drivers of biodiversity loss and protecting freshwater areas, to health innovations for the Global South - and much more. Let our Champions motivate you to help save our planet! You can read the 2023 FPP Champions' work in our first Collection here.



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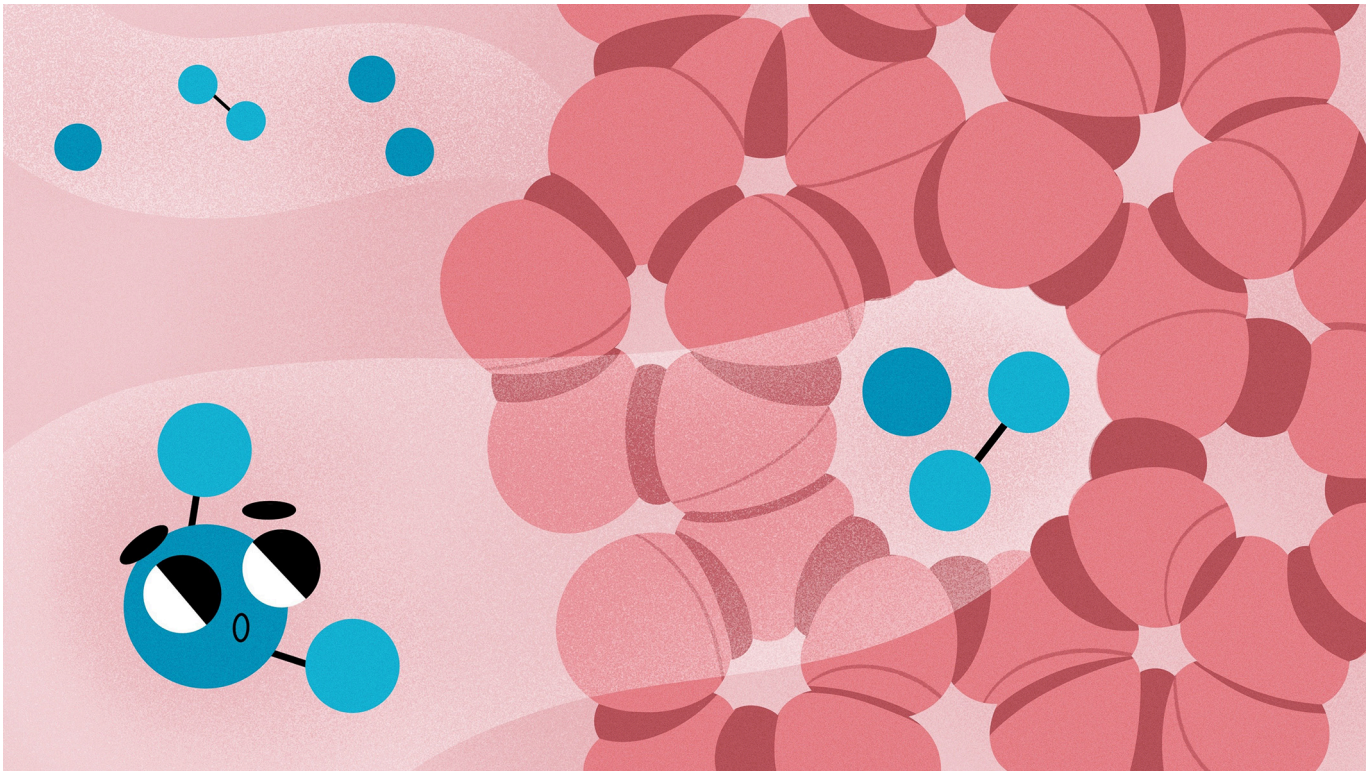

TURNING CO_2 INTO USEFUL PRODUCTS: THE ROLE OF CATALYSTS IN PROTECTING OUR PLANET

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YOUNG REVIEWERS:


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AGE: 14


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AGE: 13


BILAL
AGE: 15


ELENA
AGE: 14


SAMAR
AGE: 8

Climate change is one of the biggest problems our planet faces, caused by too many greenhouse gases (GHGs) in the atmosphere. The most important GHG produced by humans is carbon dioxide (CO_2). To slow down global warming, we need to reach net zero CO_2 emissions by balancing the amount of CO_2 we release with the amount we remove. One exciting way to help us to do this is by turning CO_2, often seen as waste, into useful products and energy. To make this possible, scientists use special substances called catalysts. In this article we show how some amazing materials like zeolites and OMS (ordered mesoporous silica) can act as catalysts to help transform CO_2 into valuable products and energy, opening up a new way to protect our planet and helping to fight climate change.

ROLE OF GREENHOUSE GASES

Greenhouse gases (GHGs) in the atmosphere help control Earth's temperature and climate. They act like a blanket, keeping Earth warm enough for life (Figure 1A). Without GHGs, the Earth would be freezing, and humans, animals, and plants would not be able to survive.

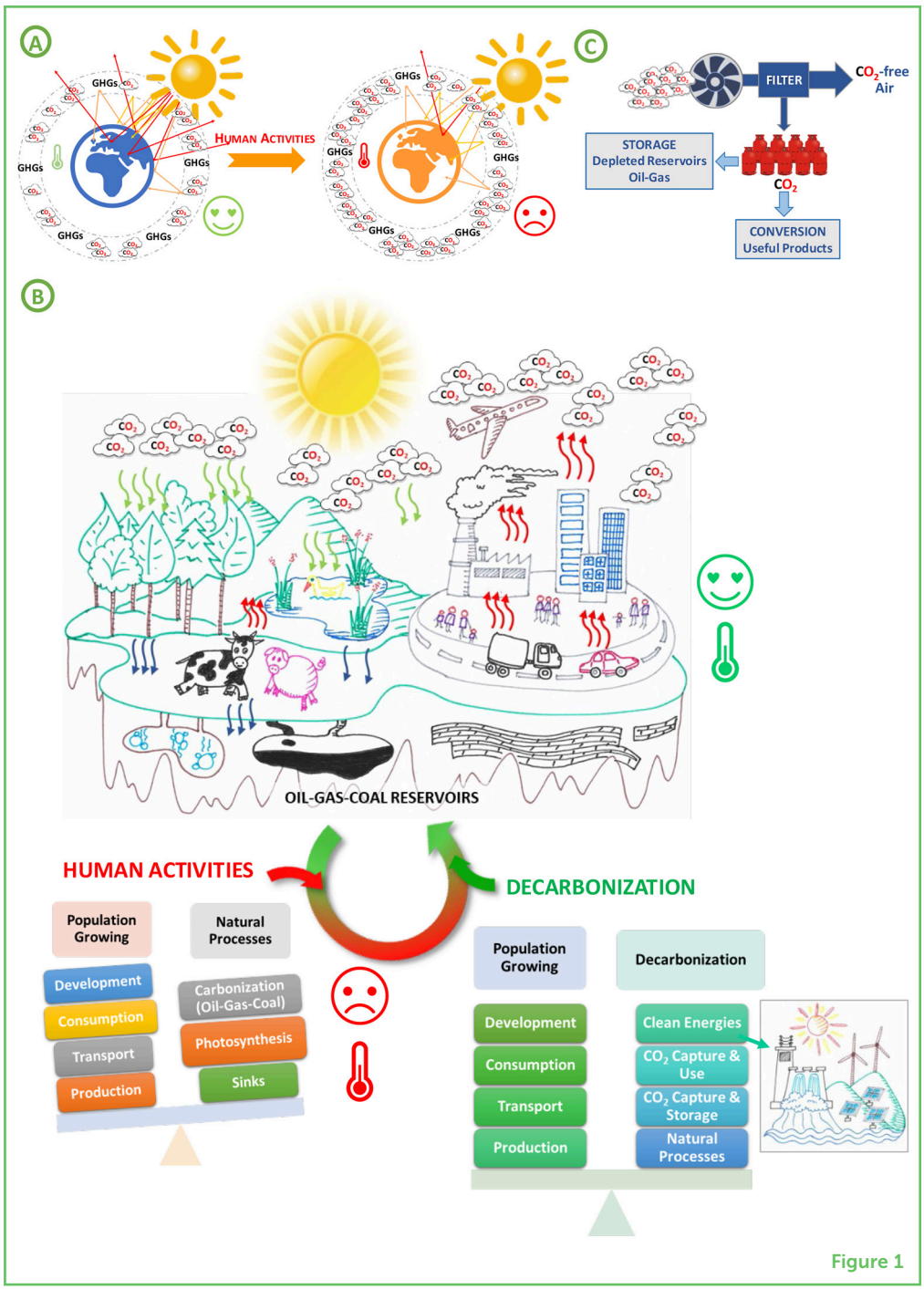

Figure 1

(A) GHGs in the atmosphere help to control the Earth's temperature. **(B)** Human activities like consumption, production and transportation are adding more and more CO_2 to the atmosphere, leading to an increase in the global Earth's surface temperature. Balancing the amount of CO_2 is possible by decarbonization processes that allow a return to a favorable global Earth's surface temperature. **(C)** Decarbonization process involves taking directly CO_2 from air or from the fumes released by factories. This CO_2 can be stored underground or used as a building block to create useful products (Figure credit: Pablo A. Ramos).

The main GHGs are water vapor (H_2O), carbon dioxide (CO_2), and methane (CH_4). These gases have naturally existed for millions of years, and they all play a role in making life possible. However,

human activities like consumption such as the use and such as the use and spending of goods, services and activities in order to satisfy human needs, production of goods in factories, and many forms of transportation are adding more and more GHGs to the atmosphere (Figure 1B). This leads to increase global Earth's surface temperature influencing on climate change, which harms ecosystems, reduces biodiversity, and causes problems like acidic ocean waters, which threaten the entire food chain (Figure 1A).

CO_2: THE MAIN GREENHOUSE GAS

CO_2 is the most important GHG produced by humans. It remains in the atmosphere for a long time, hundreds or even thousands of years. Natural processes called carbon sinks can remove CO_2 from the air (Figure 1B). For example, photosynthesis, which is the way plants absorb CO_2 and convert it into oxygen and food, is a carbon sink. Natural absorption of CO_2 by the oceans and geological processes such as absorption of CO_2 by rainwater or reaction with rocks and soil to form new minerals over thousands of years are other examples of carbon sinks.

Unfortunately, however, these natural processes are not fast enough to absorb the additional CO_2 that humans are continually adding to the atmosphere.

WE NEED TO ACT NOW!

Scientists agree that to stop global warming, we must reach what is called **net zero** CO_2 emissions by 2050. Net zero means balancing the amount of CO_2 we release with the amount we remove from the atmosphere, so no extra CO_2 builds up. But reaching "zero emissions" is extremely difficult. Think about how much we depend on cars, planes, factories, and even electricity, which often generate CO_2. So, we have to explore solutions to remove CO_2 that is already in the air.

NET ZERO

Means to balance a scale. If we add something, we have to subtract the same amount to maintain the value, i.e., the balance is zero.

DECARBONIZATION APPROACHES

Scientists have been working for several decades on various strategies to reduce CO_2 emissions and to remove it from the atmosphere—a process known as **decarbonization** (Figure 1C). One approach is based on directly capturing CO_2 from the fumes released by factories and storing those gases, in a process called **sequestration**. For CO_2 storage, permanent reservoirs are used, such as deep underground geological formations, like depleted oil and gas reservoirs or saline aquifers. Another method of decarbonization is to plant trees to create woodlands or to replant forests that have been cut down.

DECARBONIZATION

Means stopping the increase in the amount of carbon in the air.

SEQUESTRATION

Means catching and keeping in storage.

Furthermore, over the last 20 years, scientists have been exploring an exciting new method of decarbonization: using CO_2 as a building block to create useful products and energy.

WHY USE CO_2 TO MAKE USEFUL PRODUCTS?

Carbon (C) is one of the most important building blocks of life. It is found in all living or formerly living things, like plants, animals, and even in your food. Carbon is also in many man-made products we use every day, like plastics, furniture, clothing, paints, medicines, cosmetics, and fuels. What makes carbon so special is its ability to form strong bonds with itself and with other elements like oxygen (O), nitrogen (N), and sulfur (S). These strong bonds allow the creation of all kinds of natural and man-made materials (Figure 2A).

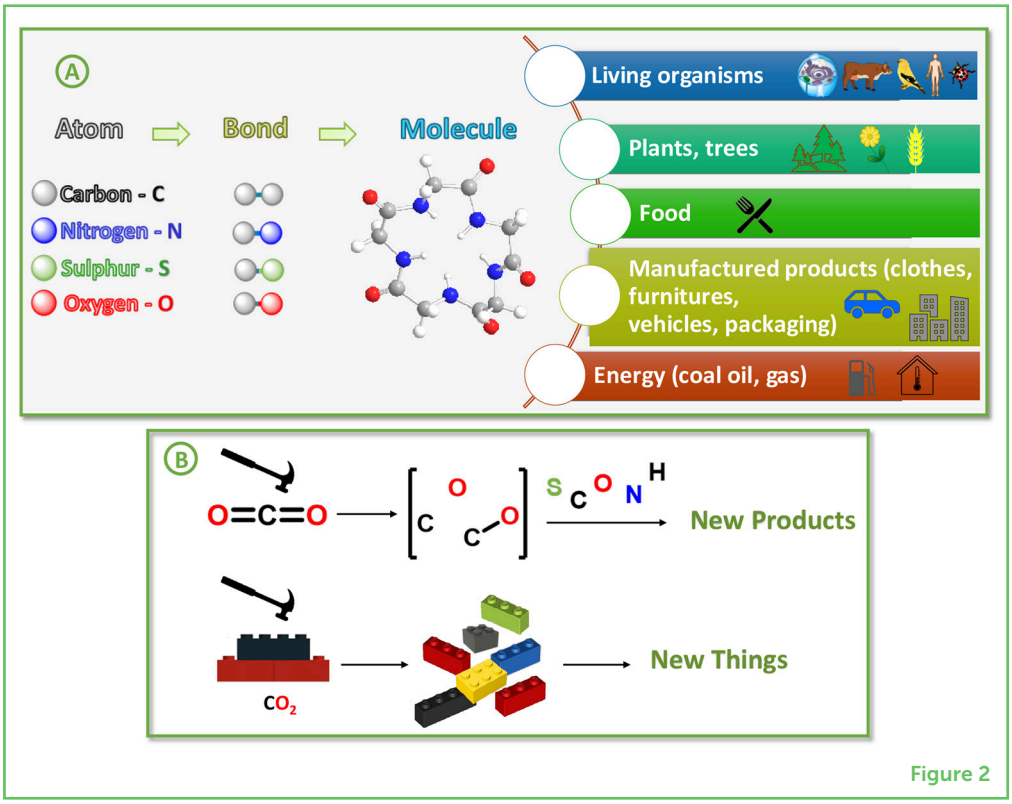

Figure 2

(A) Carbon can form strong bonds with other elements, creating many natural and man-made products. **(B)** Breaking the strong bonds of CO_2 to free up the carbon and oxygen atoms can allow those atoms to be recombined to produce new products. You can think of this like breaking apart Lego pieces to create new structures.

CO_2, the gas we usually think of as waste, is actually a great source of carbon. Therefore, scientists are finding ways to take the carbon locked up in CO_2 and use it to make useful things (Figure 2B).

WHY IS IT HARD TO TRANSFORM CO_2?

CO_2 is a super stable molecule. Its carbon (C) and oxygen (O) atoms are tightly bonded together, like LEGO pieces firmly clicked together. Breaking these bonds and rearranging the atoms to create new molecules requires a lot of effort, which means that the chemical

transformation of CO_2 into something new is a big challenge. To overcome this barrier and make this process easier and faster, chemists use powerful tools called **catalysts**.

CATALYSTS CAN HELP WITH DECARBONIZATION

A catalyst is a substance that speeds up chemical reactions without being used up or changed. Catalysts encourage molecules to lock together and form new products by reducing the efforts needed for the reaction. Catalysts have special parts called **active sites**. These are like tiny pockets or shapes where the catalyst and the molecules that are reacting fit together perfectly, like puzzle pieces. When the molecules fit into the active sites, the reaction happens, and the molecules are transformed into something new. The active site makes the reaction faster and easier, without running out, so it can keep helping over and over (Figure 3A).

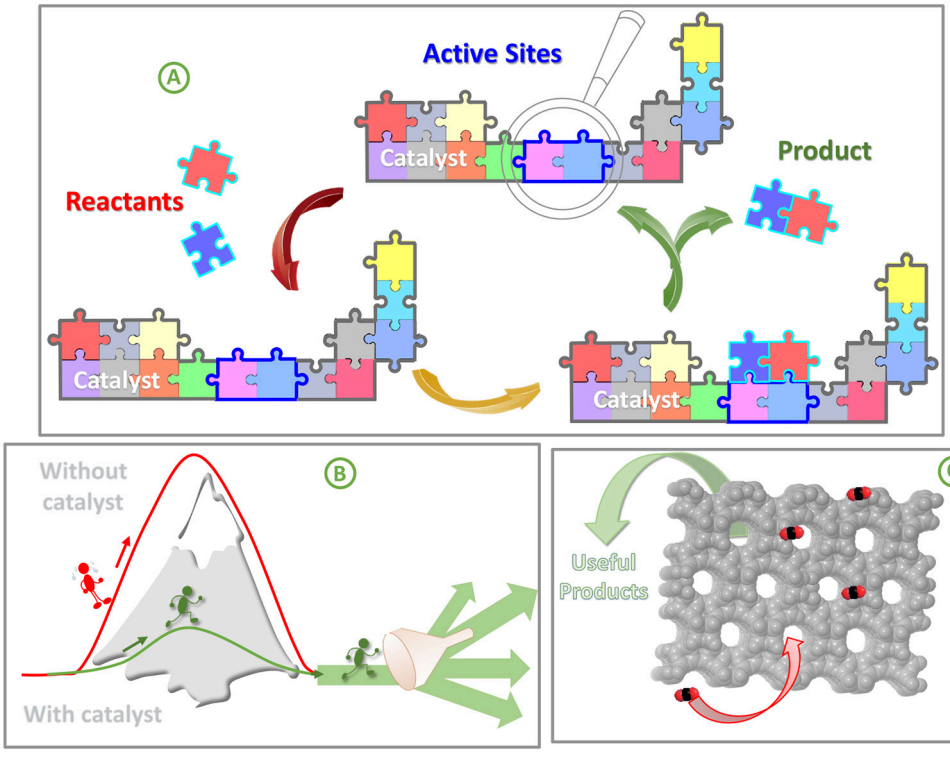

Figure 3

Good catalysts do not just speed up reactions—they also direct the reactions to make the "right" products and avoid unwanted production of unnecessary by-products (Figure 3B). This property, called **selectivity**, is key to making chemical processes more efficient and eco-friendly.

Catalysts can have different forms and state, can therefore be solids or liquids. Solid catalysts are easier to work with because they

CATALYST

Is a special substance that accelerates chemical reactions without being used up. Catalysts encourage molecules to lock together and form new products by reducing the efforts needed for the reaction.

ACTIVE SITES

Are like little shapes in which the catalyst and the molecules fit together perfectly. This is when the reaction takes place and the molecules are transformed into something new.

Figure 3

(A) Catalysts have active sites, which are special parts where the catalyst and the molecules to be reacted fit together perfectly like puzzles pieces. **(B)** Catalysts not only make reactions easier and speed them up but also direct them along selective pathway to obtain the desired products. **(C)** Catalysts like zeolite and OMS have tiny pores and channels that act like a molecular sieve and can choose which molecules to trap and react based on their molecular size, and drive the reaction toward the preferred products.

SELECTIVITY

Catalysts not only accelerate reactions, but also direct them to obtain the right products and avoid the production of unnecessary by-products. This property is called selectivity.

can be easily separated from liquid mixtures by filtration, the same way we separate pasta from water using a strainer. By making the transformation of molecules like CO_2 more efficient, catalysts save energy, reduce costs, and help lower CO_2 emissions.

CATALYSTS IN DAILY LIFE, SCIENCE, AND INDUSTRY

Catalysts are all around us. For example, we have natural catalysts called enzymes in our bodies, which act as natural catalysts, helping to break down food into nutrients. Similarly, the yeast used in baking bread and biscuits acts as a catalyst to create the tiny bubbles that help the dough rise and become fluffy.

Scientists have made great discoveries in recent decades and have learnt how catalysts work. They explored the influence of catalysts on reaction conditions (e.g., heat, time, and ingredients) and rate. Moreover, the advances in technology and devices allow to study and monitor reactions at incredibly small scales, down to the level of molecules (microscope), nanostructures (1000 times smaller) or even single atom [1].

Catalysts are powerful tools that help chemists overcome the challenges of transforming molecules such as CO_2 into useful products—all while saving energy and sources, reducing CO_2 emissions, and protecting the planet [2]. Today, catalysts play a crucial role in producing over 80% of products we use, making them vital for industry and the economy. In the future, catalysts will be even more important for creating clean water, renewable energy, sustainable food supplies, and eco-friendly products.

But catalysts are not just tools for chemists, they are amazing tools for building a better world.

ZEOLITE

Are tiny crystals called molecular sieves because of their pores and channels of microporous dimensions that act like a sieve, selecting which molecules to trap and react depending on their size.

ORDERED MESOPOROUS SILICA

Are tiny crystals called molecular sieves because of their pores and channels of mesoporous dimensions that act like a sieve, selecting which molecules to trap and react depending on their size.

ZEOLITES AND OMS: POWERFUL CATALYSTS

Zeolites and **ordered mesoporous silica** (OMS) are special materials mostly made of silica, a substance similar to beach sand. What makes these materials unique is their amazing structure. They are like super tiny sponges, full of microscopic pores and channels that are measured in nanometers (one billionth of a meter) (Figure 3C). Because of these tiny openings, zeolites and OMS are also called "molecular sieves" because they can sort molecules by controlling which can pass through them or get trapped inside, based on the size of the molecules. It is like trying to pass balls of different sizes through a sieve: the smaller ones go through, but the bigger ones do not. In this way, these catalysts can choose which molecules to trap and react, to drive the reaction toward preferred products according to their molecular size. Zeolites and OMS can have different shapes, types, and

a huge variety of active sites. These adjustable characteristics allow scientists to customize their powers.

For over 100 years, zeolites and OMS have been used in industries for all sorts of tasks. They have helped make gasoline, clean water, and purified air. For the past 25 years, we have prepared powerful catalysts from these materials in our laboratory and used them for the eco-friendly manufacture of useful products, thus helping to protect the planet. These incredible materials may be tiny, but they are making a big difference in solving some of the world's most difficult challenges.

ZEOLITE AND OMS CAN CONVERT CO_2 INTO USEFUL PRODUCTS

In our laboratory, we have a lot of experience in the design and preparation of powerful catalysts from OMS and zeolites. We work on improving the performance of zeolite and OMS by creating powerful and sophisticated active sites for challenging transformations. These catalysts help us to transform CO_2 into useful things, like methane, a fuel that can power homes and vehicles [3]. We also explore the possibility of preparing other valuable products. But in this quest, we must be careful that CO_2 conversion does not use too much energy or too many raw materials, or the reactions can produce more CO_2 than they save! As our work advances, powerful zeolites and OMS will be game-changers in the mission to recycle CO_2 and turn it into something valuable.

In conclusion, zeolites and OMS are powerful tools that can be specifically designed to help us turn CO_2 from waste into useful products and energy. These catalysts are helping us find exciting new ways to reduce CO_2 emissions. However, no single solution is enough. We must combine efforts like capturing, reusing, and most importantly producing less CO_2 to protect our planet and create a better future!

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3. Velty, A., and Corma, A. 2023. Advanced zeolite and ordered mesoporous silica-based catalysts for the conversion of CO_2 to chemicals and fuels. *Chem. Soc. Rev.* 52:1773–946. doi: 10.1039/D2CS00456A

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YOUNG REVIEWERS

AKSHARA, AGE: 14
I am a 14 year old who loves science and is enthusiastic to learn new things!

ALI, AGE: 13

I am Ali, I am 13 years old, and I like playing video games and having fun with my friends and family. I am deeply interested in Science and Engineering, and I plan to pursue a doctorate in Chemical Engineering as my career inspiration and then teach kids through much simpler ways, may be through new innovations and tools and may be only using video games to do math and science.

BILAL, AGE: 15

My name is Bilal. I am deeply interested in medicine and engineering, and I love research, I am fascinated by how stem cells can repair certain cells, tissues and diseases. I am currently working on stem cell model systems. As my lifelong goal I plan to pursue medicine but with deep insights and expertise in mathematics and engineering.

ELENA, AGE: 14

My name is Elena. I love learning about biology, anatomy and medicine. My hobbies and favorite things to do include reading, making jewelry and rowing. I have competed at 2 National Championships and Head of the Charles Regatta, placing top 5. It is a great sport to combine scientific and critical thinking with athletics. My favorite classes are Biology and Anatomy and Physiology. I hope one day to work in the medical field and do medical research to contribute to my community.

SAMAR, AGE: 8

I am Samar, and I like playing with my friends and making friendship clubs. I am the president of a friendship forever club at my elementary school. I love going to my school library and looking at books. On weekends I always push my mom to take me to our neighborhood libraries as for me it is fun to just look at pictures in nice books about sea creatures and oceans. I am fascinated by living systems, particularly how life came into being in oceans and researching on Sharks and Whales. I love asking lots of questions to my teachers and parents. I also love Disney world and hope to continue visiting it every year, its lot of fun and inspires me to dream.

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Dr. Alexandra Velty graduated in Chemical Engineering from the University of Rennes and in Chemistry from the University of Nancy (France). She completed her PhD at the Polytechnic University of Valencia (2003), Spain. Currently, Dr. Velty is a permanent member of the Polytechnic University of Valencia. Her research focuses on advancing sustainability through the design, synthesis, and application of solid catalysts. She specializes in the re-engineering of industrial processes and the use of renewable resources for the sustainable production of chemicals and energy. *avelty@itq.upv.es

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RIVER INVERTEBRATES SHOW THAT EUROPEAN FRESHWATER HABITATS HAVE STOPPED IMPROVING

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YOUNG REVIEWERS:

HARMONY
AGE: 13

JACK
AGE: 10

Freshwater habitats have been harmed by pollution. People tried to fix this problem by reducing pollution from cities and farms, but we do not know if these efforts worked. To find out if they did, a group of scientists caught small animals, called invertebrates, from rivers across many European countries. Invertebrates can tell us if a river is polluted because we catch many different invertebrates in unpolluted rivers, but only a few in polluted rivers. If more invertebrates are caught each year, it means rivers are getting better. Researchers caught more invertebrates during the 1990s and 2000s. This was good news because it showed that reducing pollution helped many rivers. However, they did not catch more invertebrates in the 2010s. This means rivers stopped getting better, maybe because of other problems we have not fixed, like climate change. More work is therefore needed to help freshwater habitats improve again.

FRESHWATER HABITATS ARE IN TROUBLE

Freshwater habitats, like rivers, lakes, and ponds, are very important. Many different **species** (kinds) of animals and plants live in these habitats. Freshwater habitats also provide people with drinking water, food from fishing, electricity from waterpower, and places to play and enjoy nature, like swimming and canoeing. However, freshwater habitats and the species that live there are in trouble. People like to build cities near freshwater habitats and use surrounding land for farms. Building and farming can harm freshwater habitats. **Wastewater** from our buildings, yards, and roads can also pollute them.

Many countries have tried to fix these problems in various ways. One common way is to build wastewater treatment plants. These are large buildings that collect wastewater from cities to remove chemicals and other harmful substances. Other helpful actions include reducing **pollution** from factories and cars, and using fewer fertilizers and pesticides on farms. These fixes can help, but we do not know whether they are helping as much as we need them to [1, 2]. We need data that can tell us if freshwater habitats and their species have improved. These data must come from many countries because we need to know what is happening *everywhere*, not just in one place.

INVERTEBRATES CAN TELL US ABOUT FRESHWATER HEALTH

To find out what has happened to freshwater habitats and species, a group of scientists caught **invertebrates** from many European rivers [3]. Invertebrates are small animals that do not have backbones, such as insects like dragonflies, and other animals like snails and worms. River invertebrates tend to live underwater, especially under rocks or in mud at the river bottom. We collect river invertebrates because these animals have been used for more than 100 years to tell us how healthy a river is. How? Invertebrates are the most species-rich animal group on Earth, and many of these species cannot live in polluted rivers. We therefore find a lot of invertebrate species in healthy rivers, but only a few species in polluted rivers. If we catch river invertebrates every year and find more each year, it means rivers are getting better. If we do not catch more, it means rivers are not getting better, and if we catch less, it means rivers are getting worse.

CAPTURING RIVER INVERTEBRATES

Scientists catch river invertebrates by going to the same part of a river each year, during the same season, kicking their feet along the river bottom, and trapping invertebrates in nets (Figure 1). This is simpler than testing the water because there are many different pollutants and

FRESHWATER HABITAT

Places with water that is not salty, where animals and plants live. Examples are rivers, streams, wetlands, lakes, and ponds.

SPECIES

A group of animals, plants, or other living things that are alike and can reproduce with one another.

WASTEWATER

Water that has been used by people, such as in factories or houses.

POLLUTION

Harmful material in water, air, and soil. Polluted water is not healthy to drink or swim in.

INVERTEBRATES

Small animals that do not have backbones, such as insects like dragonflies, and other animals like snails and worms.

Figure 1

(A) Example of a scientist collecting river invertebrates by kicking or sweeping along the river bottom. **(B)** Invertebrates are captured in large nets. Examples of invertebrates that can be found in European rivers and streams include **(C)** freshwater mussels and **(D)** stoneflies.

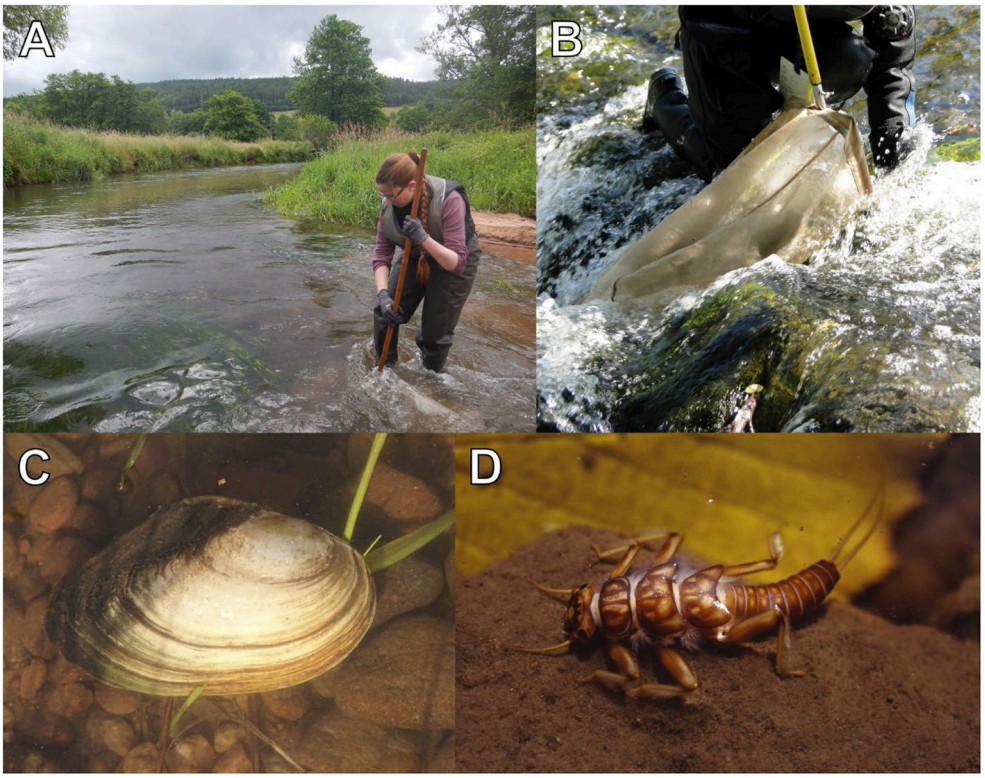

Figure 1

chemicals that could be affecting a freshwater habitat, making testing difficult and very expensive. Instead, it is easier and cheaper to collect invertebrates and use them to tell us if the water is generally good or bad.

River invertebrates were caught from 1,816 different sites in rivers from 22 European countries. The sites are in countries like Denmark, France, Germany, and the United Kingdom. All invertebrates were caught between 1990 and 2020, although invertebrates were caught at each site in different years. For example, invertebrates were collected from one river in Denmark from 1999 to 2016, and in a different river in France they were collected from 1992 to 2017.

RIVERS STOPPED IMPROVING AROUND 2010

To find out if more invertebrates were being caught, the scientists measured the average percent change in the number of invertebrate species caught each year across all sites. They did this only for 1995 to 2016 because they did not have enough data from other years. For each year, if the number was above 0%, it meant they caught more invertebrates compared to the previous year. This would mean rivers improved. If the number was close to 0%, it means the scientists did not catch more invertebrates and rivers did not improve compared to the

previous year. If the number was below 0%, it means scientists caught fewer invertebrates and rivers got worse.

The scientists found that the number of invertebrate species in rivers increased in the earlier years of their work, during the 1990s and 2000s. However, in later years during the 2010s, they did not find more invertebrates (Figure 2).

Figure 2

Percent change in the number of invertebrate species each year. Numbers were around +1% before and up to 2010 (blue circles), showing that rivers were gaining species and thus were improving. However, the numbers shifted closer to 0% after 2010 (red circles), showing rivers stopped gaining new species and thus stopped improving.

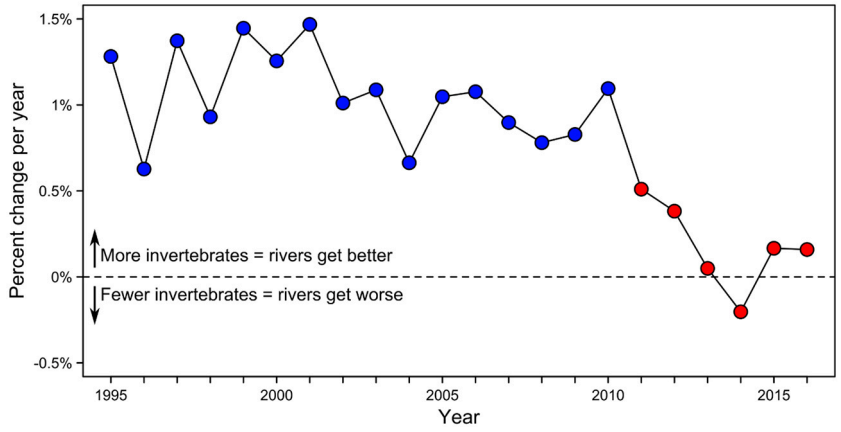

Figure 2

Catching more invertebrates during the 1990s and 2000s means that European rivers got better during these years. This is an important finding because it shows people can help fix freshwater habitats and species, even if those habitats have been harmed in many countries. Improvements likely happened because of our efforts to clean up pollution in rivers. For example, many European countries use wastewater treatment plants to reduce pollution from cities. Many places have also increased the amount of river habitat. This can happen by removing dams or by planting trees along the riverbank to provide shade and food for river invertebrates.

Catching fewer invertebrates during the 2010s means that rivers *did not* continue to improve during this time. This data could even be an early warning sign that rivers may become worse in the future.

WHY HAVE RIVERS STOPPED IMPROVING?

DIVERSITY

The number of different species.

There are many reasons why rivers may have stopped getting better. One reason could be that invertebrate **diversity** is now at its maximum in many rivers. However, this explanation is unlikely because most monitored freshwater habitats across Europe still have a lot of room for improvement [4]. An alternative explanation is that, while people have fixed some problems, other problems have not been fixed. For example, pollution from cities is lower, but rivers are still being polluted by farms. The increasing size of the human population also means more water is being taken from rivers for human use. Many countries

are making laws right now to try to fix this [5]. Some problems have also gotten worse in recent years, such as climate change. Increasing temperatures from climate change, along with more floods and droughts, can harm river species [6]. These problems need to be fixed. We must keep working hard to help rivers improve again. By making rivers healthier, we help both the people who use rivers and the species that live in them.

ORIGINAL SOURCE ARTICLE

Haase, P., Bowler, D. E., Baker, N. J., Bonada, N., Domisch, S., Garcia Marquez, J. R., et al. 2023. The recovery of European freshwater biodiversity has come to a halt. *Nature* 620:582–588. doi: 10.1038/s41586-023-06400-1

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YOUNG REVIEWERS

HARMONY, AGE: 13

Harmony is a 12-year-old that loves birds, biology, and stick figures. Some of her favorite hobbies include birdwatching, bird photography, reading, and booping her bunny Spot.

JACK, AGE: 10

I am a 10-year-old 4th grader who loves video games, anime, and anything Godzilla. I also like watching YouTube videos and learning cool new things. I am really into snorkeling especially when visiting family in Hawaii. One of my favorite hobbies is cooking, especially making my signature dish: fried calamari!

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Dr. James S. Sinclair is an ecologist who researches how freshwater habitats are affected by environmental changes caused by people, such as pollution, fishing, and invasive species. He studies different habitats, including lakes, ponds, and rivers, and various species, including plankton, fish, plants, and invertebrates. *james.sinclair270@gmail.com

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EARTH SCIENCES
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FEEDING THE PLANET WHILE SAVING IT: HOW NEW FOODS CAN HELP!

Marta Kozicka [1*], ***David Leclère*** [1], ***Chris Davis*** [2], ***Andre Deppermann*** [1], ***Stefan Frank*** [1,3], ***Dylan Bos*** [1] ***and Petr Havlík*** [1]

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YOUNG REVIEWERS:

AAYUSH
AGE: 8

JESSE
AGE: 15

ZIYUAN
AGE: 10

Eating a lot of meat and dairy puts pressure on nature. It leads to deforestation, water pollution, and climate change. By 2050, there will be over 9 billion people on Earth. Without any change in the way we eat, environmental damage will only get worse. What if we could eat foods that taste like meat and milk, but without hurting the planet as much? Novel plant-based foods, like plant-based burgers or oat milk, are made to taste and feel like animal products while using less land, water, and producing fewer greenhouse gases. Traditional plant-based foods, like tofu, lentils, and chickpeas are also healthy, tasty, and better for the planet. If everyone gradually replaced half of their meat and dairy with plant-based options we could save forests, reduce emissions, and make food more affordable. Even

small changes in diet can make a big difference for the planet—and our future.

THE FOOD PROBLEM—AND A TASTY NEW SOLUTION

Imagine this: It is the year 2050, and Earth is buzzing with over 9 billion people. But there is a big challenge growing quietly—right on our dinner plates. The problem is that producing meat and dairy the way we do now is putting a lot of pressure on the planet [1]. Forests are being cut down, rivers are drying up, pollution from farming is damaging the soil and water, and many animals and plants are disappearing as their habitats are destroyed. Even though there is more food than ever, many people still go hungry [2]. We need tasty, and planet-friendly solutions before time runs out. So how can we all eat well without harming the Earth?

What if we could solve this problem by eating foods that look and taste like meat and dairy but are made from plants? Picture biting into a burger that looks, smells, and tastes like meat—but it is actually made from plants! This is already happening. These new foods, called **novel plant-based foods**, are made to feel just like eating meat or drinking milk. The plant-based food scene is expected to grow about 10% every year over the next decade—so you will see even more awesome options like chicken-free nuggets, oat milk ice cream, and even bacon made from mushrooms.

How is this possible? It all starts with plant **proteins**—usually from plants like soybeans or peas—which scientists and food developers transform into something that looks and tastes like the real deal. They mix the plant proteins with ingredients like fats, vitamins, minerals, and water [3]. This combination helps mimic the juiciness, flavor, and texture of animal-based products. Think of tofu, which has been a traditional plant-based food for centuries. Tofu is made from soybeans and is often used as a meat substitute because it can take on many flavors and has a similar texture to some meats. Novel plant-based foods take this idea further, using science to create foods that taste even closer to the real thing!

Novel plant-based foods need fewer inputs, like land and water, compared to meat and dairy. They also produce fewer **greenhouse gases** [4]. No cows mean no methane (a greenhouse gas) burps! But how much difference would it actually make if we all gradually replaced some of our meat and dairy with novel plant-based foods? We used a powerful **computer model** to find out. This model helps scientists study how changes, like switching to plant-based foods, could impact the environment, food supply, and greenhouse gases.

NOVEL PLANT-BASED FOODS

Foods made from plants that look, taste, and feel like meat or dairy, like plant-based burgers or dairy-free milk.

PROTEINS

Nutrients our bodies need to grow and stay strong. Found in foods like meat, beans, soy, and peas.

GREENHOUSE GASES

Gases that trap heat in the air and cause climate change, like carbon dioxide, methane, and nitrous oxide.

COMPUTER MODEL

A computer program scientists use to test ideas and predict things like future food needs or climate effects.

THE PROBLEM WITH THE WAY WE EAT

First, we found that by the year 2050, producing meat and dairy will strain the planet even more than it does today (Figure 1). As the world's population grows and people earn more money, the demand for animal-sourced foods is expected to rise a lot. For example, consumption of chicken might increase by 66% and milk by 49%. To meet this demand, we will need even more farmland to feed animals. This could destroy over 250 million hectares of forests and natural areas, leaving less space for wildlife and causing more greenhouse gas emissions that drive climate change. Farming also uses a lot of water and fertilizers, which can pollute rivers and oceans. Even though some regions might see better food supplies because of new farming technologies, many poorer people could still struggle to get enough food. These challenges show why we need better ways to produce food that are healthier for the planet and fairer for everyone.

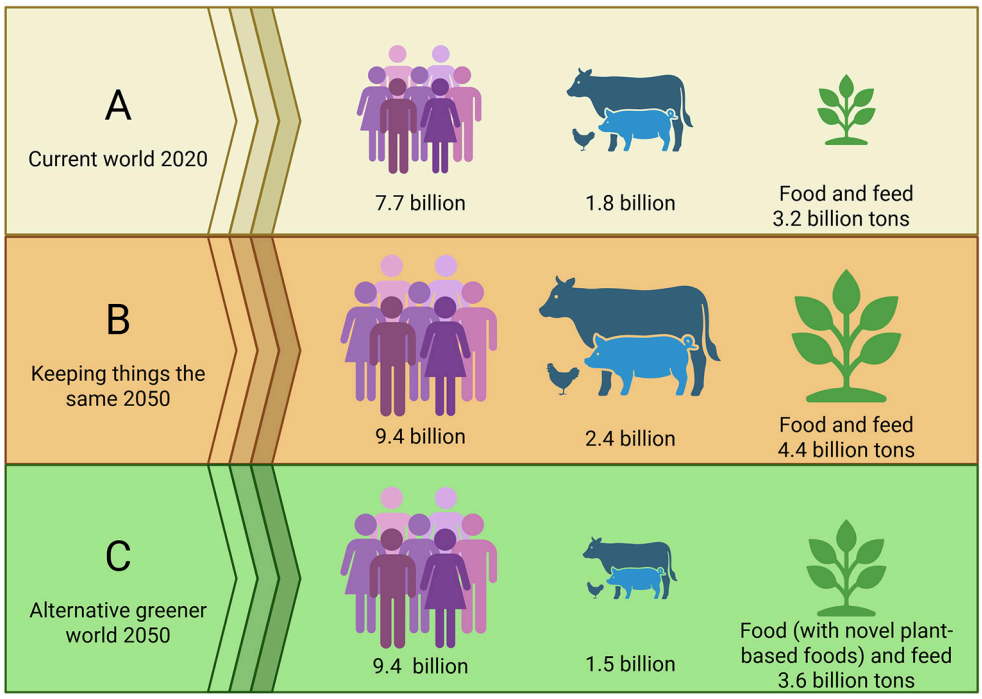

Figure 1

Figure 1

The world now and in 2050, two options for feeding the growing population. **(A)** The current food system. **(B)** The future if we do not make major changes to the way we consume food. **(C)** The future if people eat half of the main meat and dairy products compared to **(B)**. Animal numbers are presented in Tropical Livestock Units (TLUs). TLUs measure the size of a herd by counting all animals as if they were the same size, like comparing them all to one big cow. Crops are measured by weighing solid part of a crop, without the water [created in BioRender. Bos, D. (2025) https://BioRender.com/ii9kpp1].

HOW MUCH DIFFERENCE CAN NOVEL PLANT-BASED FOODS MAKE?

We then looked into alternative diets and their consequences for the planet. We found that changing our diets by replacing some meat and dairy with novel plant-based foods could bring huge benefits for the future environment. If everyone starts gradually switching their habits today, with the aim of eventually replacing just half of their animal-based foods (like meat and milk), the impacts of farming can

drop significantly. Let us have a closer look at the year 2050 in this alternative world.

First, water and fertilizer use would go down. Replacing half of animal foods with plant-based options could save 291 billion cubic meters of water per year—enough to fill 116 million Olympic-sized swimming pools! This switch would also reduce nitrogen use (in fertilizers) by 34 million tons a year, which could fill about 1.4 million large trucks. This would lead to cleaner water and healthier ecosystems (Figure 2).

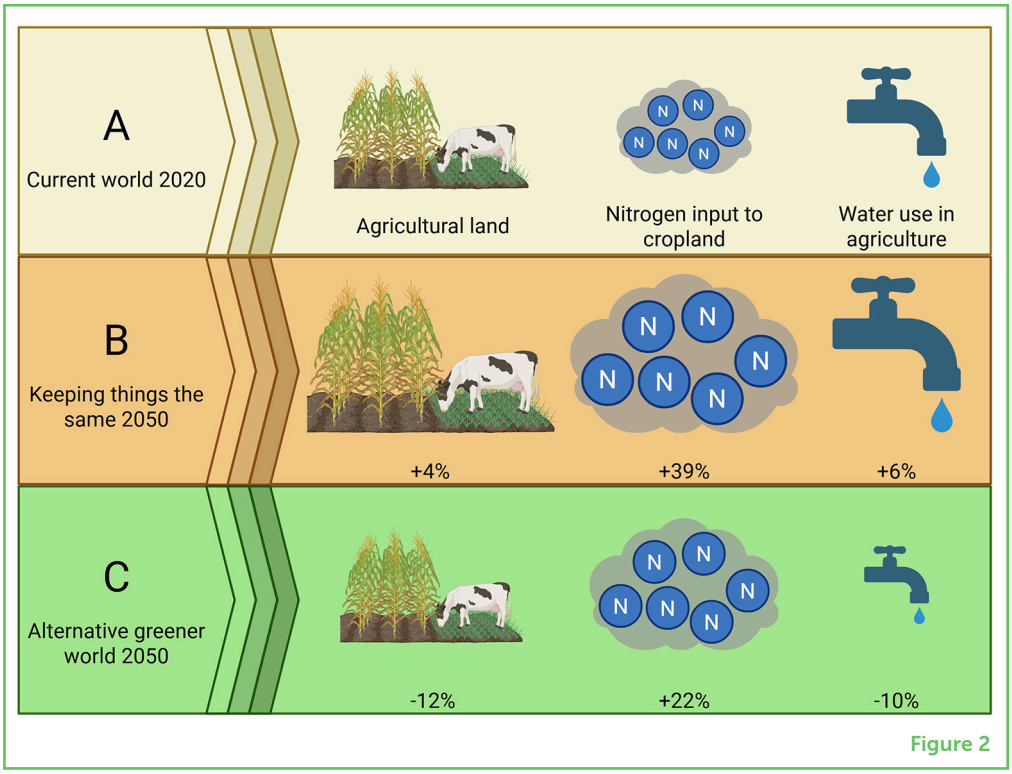

Figure 2

Figure 2

Agriculture now and in 2050, under two options for feeding the growing population. **(A)** The current food system, with land being used for growing crops for food and feed. This agriculture requires a lot of fertilizer, in the form of nitrogen, and lots of water. **(B)** The most likely future for agriculture if we do not make major changes to the way we produce and consume food. **(C)** There could be a greener future for agriculture if we lower our consumption of meat and dairy [created in BioRender. Bos, D. (2025) https://BioRender.com/twvd2e3].

Greenhouse gas emissions from farming would also drop. Farming and land-use changes, like **deforestation**, are some of the biggest contributors to climate change. Under the current path, emissions from farming are expected to rise by 15% in 2050. But with plant-based substitutions, emissions would drop by 31%—a reduction of 2.1 billion tons of **CO_2 equivalent** in 2050. This is equal to taking over 450 million cars off the road.

Another great result is that much less land would be needed for farming. That means forests and wild places could finally stop shrinking and stabilize compared to today's levels. Instead of turning more land into farms (like the 4% increase we are on track for now), we could actually shrink farmland by 12%. This would free up about 653 million hectares of land—an area nearly twice the size of India. If we go the extra mile and turn that land back into forests, the benefits get even better—we could remove an extra 3.3 billion tons of carbon dioxide from the air in 2050. That is comparable to removing about 717 million

DEFORESTATION

Cutting down forests to make space for things like farming. This can harm animals and increase climate change.

CO_2 EQUIVALENT

A way to compare different greenhouse gases by showing how much carbon dioxide they are equal to in warming the planet.

more cars! In addition, replanting forests also gives wildlife a chance to thrive and helps heal the planet. It is a big win for nature, and a big step toward saving endangered species and reaching global goals to protect our environment (Figure 3).

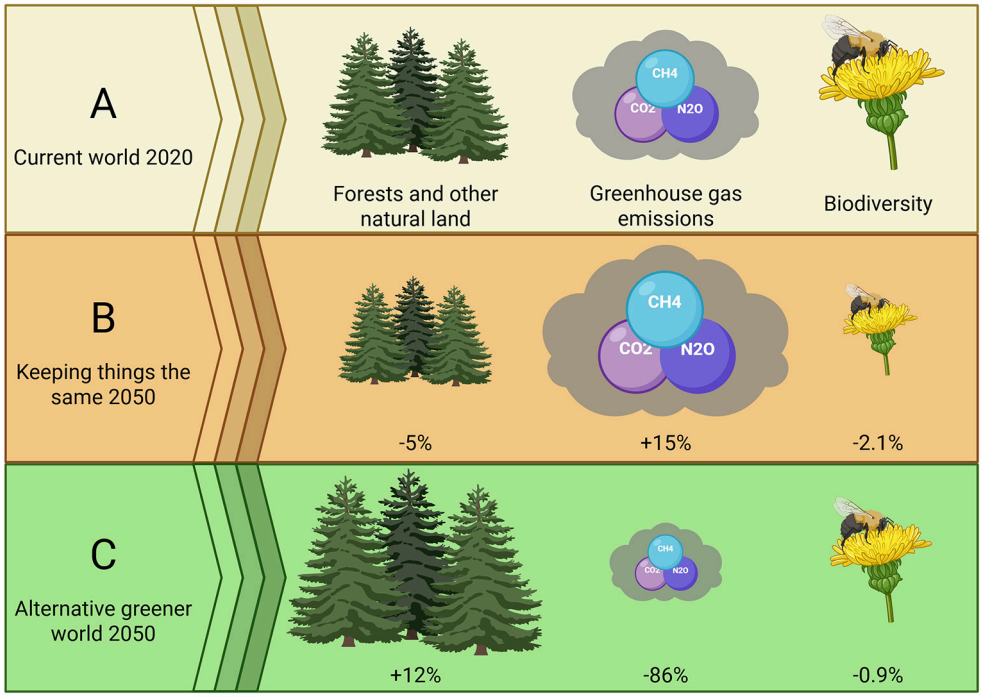

Figure 3

Figure 3

The natural environment now and in 2050, under two options for feeding the growing population. **(A)** The current natural environment. To make space for agriculture, forests and other natural lands are converted to cropland and grassland. Agriculture is responsible for a large share of greenhouse gas emissions and biodiversity loss. **(B)** The most likely future for the natural environment if we continue eating as we are. **(C)** A greener future for the natural environment, where there is less need for agricultural land [created in BioRender. Bos, D. (2025) https://BioRender.com/bgli91v].

FOOD SECURITY

When everyone always has access to enough healthy, nutritious food and no one goes hungry.

Finally, **food security** would also improve. Because crops could be grown more efficiently to feed people directly, food would become more available and cheaper. That means fewer people would go hungry. In fact, about 31 million fewer people could be undernourished—roughly the combined population of Australia and New Zealand.

It is clear that changing what we eat can make a big difference—but the effects are not the same everywhere in the world. For example, Sub-Saharan Africa, Brazil, and Latin America are key to saving forests and planting new trees, helping to lock away carbon. Even though people in these regions do not consume as much meat and milk as other regions of the world, these regions still drive more than half of global emissions reductions by 2050. There are many reasons for these differences. What matters is not only how many people live there and what they eat, but also how much food and feed they trade. We found that cutting beef consumption has some of the biggest benefits for emissions reduction and land use. As a result, countries with a lot of beef production, like Brazil, see the largest impacts.

Brazil is also home to the Amazon, the world's largest tropical rainforest, which spans several countries in South America—but the

majority, ~60%, is located within Brazil. The Amazon Rainforest is significantly affected by meat production, primarily through deforestation driven by cattle ranching and soybean farming to feed animals. This causes a lot of problems for nature and the environment. For example, it destroys habitats, leading to the loss of countless plant and animal species unique to the Amazon. Since Brazil is a major exporter of animal feed and beef, it feels the effects of dietary changes in other parts of the world. This is why changing our own food habits can save animals in the Amazon, no matter where we live!

THE FUTURE OF FOOD

Switching to plant-based foods can be challenging for some people. Many people do not think plant-based foods taste quite like the real thing, and they can sometimes be more expensive. However, as more people choose these options, companies can improve the taste and lower prices, making plant-based foods more accessible to everyone. Cultural habits are another challenge. Meat is deeply embedded in many traditional dishes and giving it up can feel like a big change. The good news is that chefs and food creators are coming up with creative ways to incorporate plant-based ingredients into familiar recipes, making the transition easier and more enjoyable.

It is really important to understand how much our food choices matter. Even small changes in what we eat can make a big difference. While our study showed that switching to novel plant-based foods would make a positive impact, this is also true for traditional plant-based foods, like tofu or legumes. They are great protein sources too. We also do not have to completely stop eating meat—skipping meat on some days of the week would be a fantastic start. Swapping out beef for more sustainable meat like chicken would also be an improvement. As we explore plant-based foods, we need to make sure to balance our diets by including a variety of nutrients to stay healthy (see here or here). Finally, as you learn more about how plant-based foods can benefit the planet, share that knowledge with others. The more people who understand the impact of their food choices on the environment, the more likely these changes will spread and help create a better future for everyone.

The future of food is exciting! With science and creativity, we can create meals that are tasty, healthy, and good for the planet. Whether it is a tofu stir-fry, hummus, or a bowl of oat milk with cereal, every small change adds up to a big impact. Together, we can feed the planet while saving it for animals, plants, and future generations.

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CONFLICT OF INTEREST: Author CD was employed by Kingdown Advisors 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

AAYUSH, AGE: 8

Hi, my name is Aayush, and I am 8 years old. I love Rubix's cubes, including Pyraminx, 2by2, 3by3, 4by4, and 5by5. I want to become a cop in the future. Going to my classes is fun.

JESSE, AGE: 15

I am a boy with a wide range of interests. I love sports, such as playing basketball, badminton, and table tennis. I like the thrill of sweating it out. I also have a passion for art. I can play the clarinet, and I love to immerse myself in beautiful melodies .I also enjoy appreciating art. I am optimistic, open, and enjoy trying new things. I am particularly interested in reviewing articles that I have never encountered before.

ZIYUAN, AGE: 10

I am Ziyuan, a 10-year-old science and biology enthusiast. I love exploring the wonders of nature, from insects in the backyard to stars in the sky. My room is my lab, I have two newts as pets. Excited to explore and learn together with everyone!

AUTHORS

MARTA KOZICKA

I am an agricultural economist, and I work as a Research Scholar at the International Institute for Applied Systems Analysis (IIASA) in Austria. In my research I focus on the ways to make the food system fair for everyone and kinder to the environment. One of the topics I am passionate about is how the foods we eat can help fight climate change and ensure no one goes hungry. When I am not working, I love exploring new foods and spaces, whether it is just around my neighborhood or in faraway places. *kozicka@iiasa.ac.at

DAVID LECLÈRE

I work as a senior researcher at the International Institute for Applied Systems Analysis (IIASA) in Austria. I use models and scenarios to explore sustainable future land use pathways. How will future human demand for biomass, crop production technologies and trade policies influence the amount of deforestation and air and

water pollution? What are related impacts on climate, ecosystems and wildlife? What measures do we need to avert on-going declines in biodiversity, and how to distribute efforts fairly across countries and actors? I am also a happy dad and husband, and I enjoy music and outdoor activities.

CHRIS DAVIS

I am a chemist who started a small company called Bayshore Creamery that makes artisanal plant-based cheeses that are delicious, lactose free and sustainable. My work revolves around different ways to use science to address the challenges of climate change and biodiversity loss. Can we develop enzymes to make chemicals with less waste? Can we create organisms that can turn waste products into liquid fuel and other chemicals? Can we recreate the deliciousness and nutrition of animal products without harming the animal and the planet? The answer is yes. In my free time, I like to spend time in nature hiking and finding delicious food to eat.

ANDRE DEPPERMANN

In University, I studied economics and during my PhD, I specialized in agricultural economics. Now, I work in Austria at the International Institute for Applied Systems Analysis (IIASA), a research institute where I use special computer models to study how people use land. My job is to explore how climate change affects our world and think about ways we can help prevent it. When I am not working, I love playing football or trying out other fun sports. I also enjoy making music and staying active in nature.

STEFAN FRANK

I am a scientist at the International Institute for Applied Systems Analysis (IIASA) where I study how land is shared between farming, forests, and bioenergy. For this, I use a simulation model and forward-looking scenarios to inform government decisions about energy, climate policies, and protecting nature.

DYLAN BOS

I work as a project manager at the International Institute for Applied Systems Analysis in Vienna, where I get to work on really cool projects on sustainability, fighting climate change, and on how to keep our ecosystems healthy. These projects are all about finding ways to make sure the Earth stays a great and healthy place for future generations, which I think is super important! When I am not working, I try to keep myself healthy too! I love cooking, reading interesting books, and I enjoy all kinds of sports, like Jiu-Jitsu, climbing, boxing, and running.

PETR HAVLÍK

I am a principal scientist working to protect nature and use our planet's resources wisely. At IIASA, I lead an interdisciplinary team that studies how we use land and how we can manage it better. I led the creation of a model called GLOBIOM, which explores how our choices affect both the environment and people's lives. My work looks at how food security, farmers' incomes, and international trade are connected to caring for nature. I have also contributed to major climate reports, all to help build a better, greener future.

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EARTH SCIENCES
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HOW REMOVING OVERGROWN WATER PLANTS CAN HELP KIDS STAY HEALTHY AND IMPROVE THE PLANET

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YOUNG REVIEWERS:

ANTONIO

AGE: 12

TOMAS

AGE: 11

In Africa, many kids get sick from tiny worms called Schistosoma. These worms can slow children's growth and development; damage the liver, intestines, and bladder; and sometimes lead to cancer or even death. Schistosoma can keep communities poor by reducing people's ability to work. Over 800 million people are at risk of infection. People get infected when they play or wash in water filled with certain plants and snails. These plants grow fast because fertilizer from farmers' fields washes into the water when it rains. We found that removing these plants can reduce Schistosoma. Plants that are removed can be turned into food for animals, compost for farms, or gas for cooking and electricity. This solution helps protect kids from getting sick and can even help to slow climate change. By working together, communities can clean their waterbodies and create a healthier, happier future, which is a win-win for people and nature.

WATER CAN BE RISKY!

Have you ever played near water, such as a stream, river, pond, or lake? It is fun to splash in the water, cool off on a hot day, or even fish. But in some parts of Africa, stepping into the water to play or wash is risky business. Tiny worms called Schistosoma live in waterbodies in Africa, and these worms can make children and adults very sick [1]. Schistosoma infections can prevent the liver, intestines, and bladder from functioning properly, sometimes leading to cancer and even death. Many children who face the risk of Schistosoma are poor and do not have electricity for their homes or enough food to eat. This story is about a win-win for people and nature: we will describe how people can work together to make waterbodies safe, keep kids healthy, and even help families have electricity and food to eat.

THE PROBLEM: SNEAKY WORMS AND OVERGROWN WATERBODIES

Schistosoma worms start their lives inside certain types of freshwater snails. Once they are ready, the worms leave the snails and swim through the water searching for people (and farm animals, like cows) to infect. The snails thrive where there are lots of underwater plants to live on. So, more plants in the water means more snails, and more snails means more worms to infect people.

Why are there so many plants in the water? It is partly because farmers use **fertilizers** to help crops like corn, rice, and lettuce grow better. Unfortunately, rain washes some of the fertilizer from farms into waterbodies, where it helps underwater plants grow really fast

FERTILIZER

A substance added to soil to boost plant growth by adding elements that plants need, like nitrogen, phosphorus, and potassium. Compost is a natural fertilizer.

(Figure 1) [2, 3]. These plants grow so much that they block water access from the shore, making it harder for people to wash, play, fish, or collect water for their homes. Worse, the extra plants mean more snails and worms, and thus more kids get sick with the disease called **schistosomiasis** [2–4]. This disease makes people tired, can make kids feel so sick that they cannot go to school, and can slow kids' growth and development [1]. We found that the more crops were being grown around a village, the more fertilizer was used and the more schoolchildren had schistosomiasis. Also, the more fertilizer that was used, the more underwater plants and snails were present, increasing the spread of schistosomiasis to people.

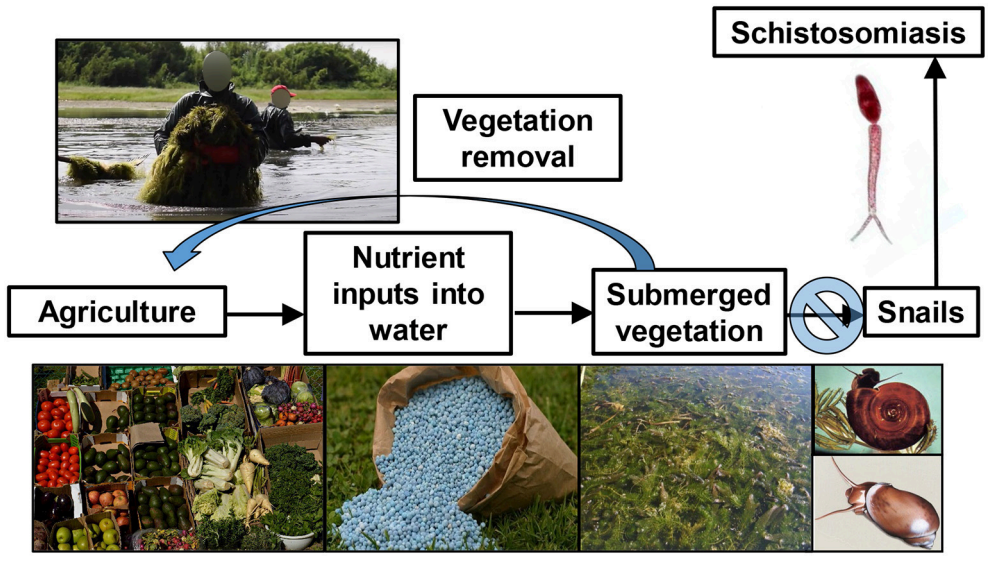

Figure 1

THE PLAN: CLEARING THE WATER

We had an idea: what if we took the overgrown plants out of the water? We tested this idea in villages in Senegal, a country in West Africa [4]. In half the villages, we used our hands (protected by rubber gloves to avoid infection) and pitchforks to remove the overgrown plants from villages' water access points, whereas no vegetation was removed in the other half of the villages. We found that the number of snails in the villages where vegetation was removed went way down relative to the villages where no vegetation was removed. Less vegetation and fewer snails meant fewer worms and less schistosomiasis in kids. The waterbodies also became easier to use. People did not have to fight through a jungle of aquatic plants to get to the water. The plant we removed is an **invasive species** that did not grow much in these areas in the past, so removing it also helps restore the original natural conditions of the region.

SCHISTOSOMIASIS

A parasitic disease caused by small worms called Schistosoma that live in freshwater snails and infect people who contact with contaminated water.

Figure 1

Hypothesized pathway by which agriculture affects schistosomiasis and the proposal to disrupt human schistosomiasis by returning nutrients captured in freshwater plants back to agriculture. We predicted that communities with more agriculture would use more fertilizer and thus have greater nutrients washing into waterbodies that promote growth of water plants. Given that water plants are habitat for snails that release Schistosoma parasites, we hypothesized that this would increase schistosomiasis. We found support for this hypothesis. So, we removed the water plants reducing schistosomiasis and returned the nutrients to captured in them back to agriculture increase food production at lower costs (Figure credits: FitNish Media on Unsplash and Anthony Trivet on Pexel).

INVASIVE SPECIES

a species that causes harm to the environment, economy, or human health.

COMPOST

Decayed plant and animal material used as a plant fertilizer.

WHAT TO DO WITH THE PLANTS?

But what should we do with all the removed plants? Instead of throwing them away, we encouraged the villagers to turn them into something useful. They used the plants as **compost** to help grow crops like onions and peppers (Figure 2), as food for sheep (Figure 3), and to generate energy for households.

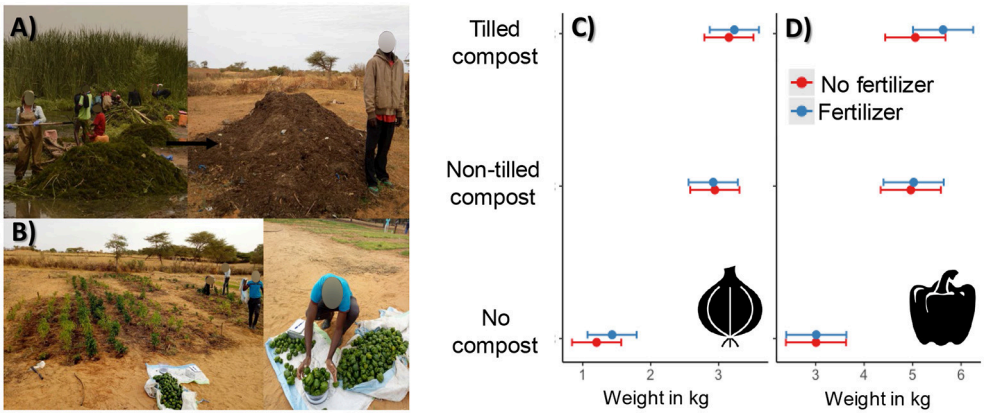

Figure 2

Figure 2

Plants pulled from waterbodies can be used as compost to increase food production. **(A)** Removed vegetation and compost piles. **(B)** Pepper plots receiving compost and fertilizer treatments, and the farmer collecting data for the project. The compost increased **(C)** onion and **(D)** pepper production, regardless of whether the fertilizer was tilled (mixed) into the soil. The dots show the means and the lines show the variation among the replicates [Figure adapted from Rohr et al. [4] with permission].

Figure 3

Figure 3

(A) Cattle and donkeys readily ate the removed plants. However, goats refused to eat them. **(B)** Sheep and feeds used in our sheep experiments. When their normal diet was replaced with up to 60% of the removed plants, the final weights of adult and juvenile sheep were similar to sheep that ate normal diets (data not shown). This tells us that the plants were not harmful. **(C)** Local communities willingly helped us to remove the plants from the water [Figure adapted from Rohr et al. [4], with permission].

Soils are very sandy in this area, so farmers add nutrients to make the soil healthy enough to grow food and to hold water for crop roots to soak up. In addition to washing into nearby waterbodies when it rains, chemical fertilizers are expensive, and their production

and use contribute to climate change. Compost, created by letting the plants naturally break down for a few months (Figure 2A), is a natural fertilizer that can improve soil health. Would the nutrients in the composted plants help crops grow as well as crops receiving chemical fertilizers? We recruited local farmers to help answer this question (Figure 2B) and we discovered that the compost worked wonders. Compost almost tripled onion production and nearly doubled pepper production (Figures 2C, D), regardless of whether the compost was applied on top of the soil or tilled (mixed) into the soil, or whether it was applied alone or with chemical fertilizer [4]. Compost helped the soil hold water and gave the crops important nutrients, even more than chemical fertilizer. Additionally, the compost reduced fertilizer pollution in the environment and cost much less than chemical fertilizers, helping farmers save money.

Just as the plants pulled from the water can feed the farmers' soil, we also found that these plants could feed their farm animals. Many livestock, such as cattle, donkeys, and sheep, were attracted to the plants and started eating them (Figure 3A). So, we tested whether the plants (dried for a couple of weeks to kill any parasites) could be used as a substitute for purchased livestock feed (Figure 3B). We discovered that both adult and juvenile sheep maintained their weight when we substituted up to 60% of their diets with the plants we removed from nearby waterbodies (Figures 3C, D) [4]. Thus, the plants were not harmful to the sheep, and they cost much less than purchased animal feed.

BIODIGESTER

A tank in which microorganisms break down waste and produce fertilizer and gas that can be used to generate electricity.

We also mixed the plants with cow poop in **biodigesters**. Biodigesters use microorganisms to turn plant and animal waste into gas that can be used for cooking or electricity production. This is useful because many homes in Senegal do not have gas or electricity and more than 80% of households use firewood and charcoal as cooking fuel. With cleaner biodigester gases, families did not need to cut down trees and burn wood to cook their food, which can make the air cleaner. Additionally, when cow poop breaks down, it can release methane, one of the most powerful gases changing our climate. We found that combining the plants with cow poop in biodigesters produced high-quality gas, minimizing the amount of methane released while also providing homes with the energy they needed to cook their food. Biodigesters powered by these plants keep trees standing and air clean, while feeding people and helping slow climate change.

WHY IT MATTERS

This simple idea of clearing overgrown plants in this region of Africa has multiple benefits [4, 5]. First, it helps protect kids from getting sick with schistosomiasis. Second, it makes waterbodies easier to access and safer to use. Third, it helps farmers save money while growing more food. Fourth, it can help to provide households with cleaner

energy. Fifth, it can reduce pollution, deforestation, and climate change, all of which can be harmful to animals and people. Finally, it can improve lives by helping communities escape from extreme poverty. Actions that have multiple benefits are sometimes called win-win solutions; in this case, there are so many wins!

WORKING TOGETHER FOR A BETTER FUTURE

When we started removing the plants, many people in the communities joined in to help (Figure 3E), not just because it made the water safer but also because it provided many other benefits. We are now training communities to keep their waterbodies clear and how to turn the plants into a resource. In a partnership with these same communities, we are searching for ways to improve this process and are co-developing new knowledge to enhance their lives. By working as a team, the communities can keep their waterbodies clean and their families healthy. We are now using satellites to find which waterbodies have too many plants, so we know where to target our efforts next.

WHAT CAN WE LEARN?

Too often, people develop solutions to big problems without considering potential negative side effects or multiple benefits. This story teaches us that, if we are creative and open-minded, there might be relatively simple solutions to some serious problems. This story also shows how people can work together to create a healthier world for humans, plants, animals, and soils—a concept called **planetary health**. We hope this work inspires new ideas for win-win solutions that are positive for both nature and people. Next time you see a waterbody, think about how important it is to keep it clean and healthy and that a little teamwork can go a long way in making our planet a better place for children everywhere! (To learn even more, please check out our project website).

PLANETARY HEALTH

a concept that recognizes that human activities, such as climate change, deforestation, and pollution, have a significant impact on the environment and, in turn, on human health.

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David López-Carr is a professor of geography at the University of California, Santa Barbara. He examines potential win-win outcomes for people and the environment. He has authored over 220 publications thanks to over 50 fellowships and grants from NASA, NOAA, NSF, NIH, and numerous other sources. López-Carr is an AAAS Fellow and was awarded the *Research Excellence Award* from both the Population Specialty Group and the Human Dimensions of Global Change Specialty Group of the Association of American Geographers, as well as the AAG *Excellence in Mentoring Award* and the Conference of Latin American Geography *Teaching Award*.

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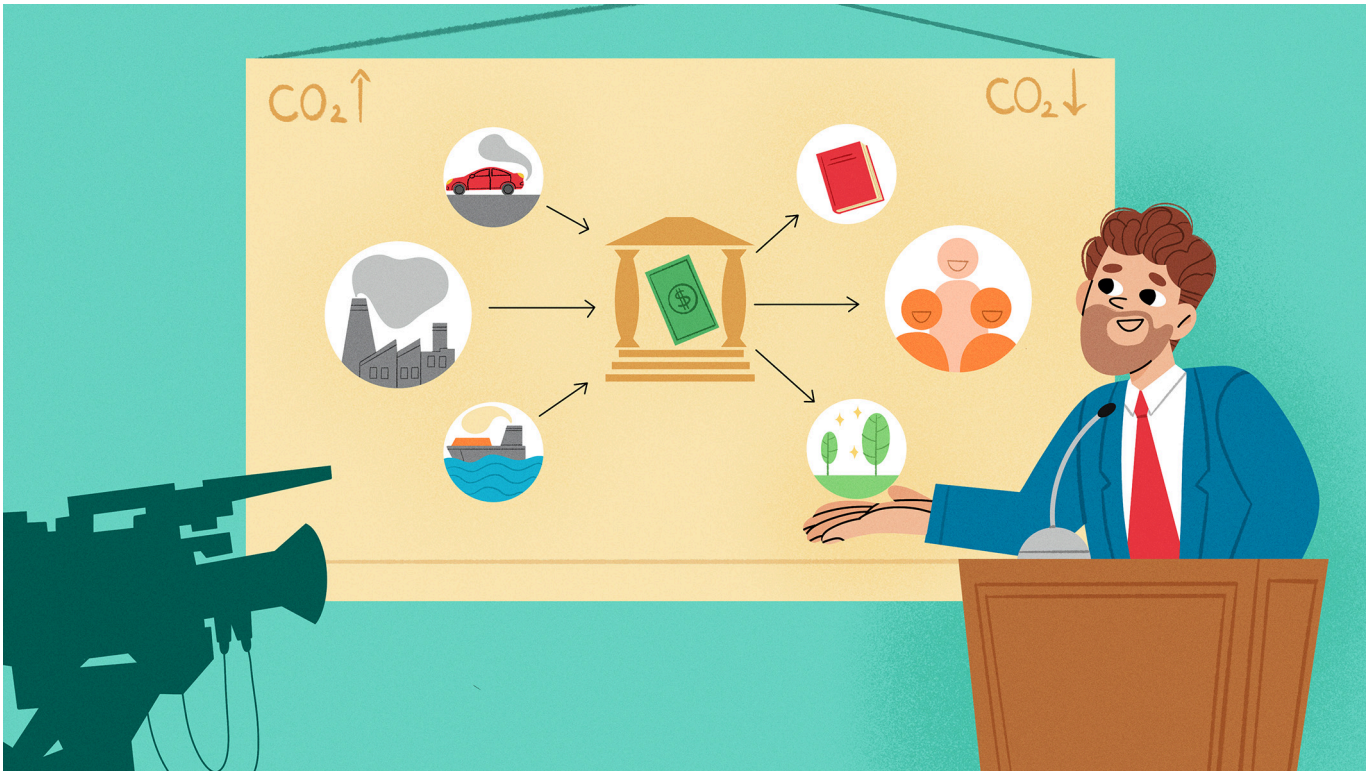

HOW CAN WE GET POLITICIANS AND COMMUNITIES TO SUPPORT CLIMATE ACTION?

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YOUNG REVIEWERS:


SIDDHANT
AGE: 12


TAHMID
AGE: 13


TAHIYAT
AGE: 11


TANVIR
AGE: 14

Scientists generally agree that making companies pay for their own greenhouse gas pollution is effective. This is called paying carbon tax, and the tax can help fight climate change by making people want to burn less polluting fuels, for instance, by using electric cars or solar panels for heating. However, most countries that charge carbon tax do not charge enough money to make big changes. This is because the governments worry that people will say the extra taxes are unfair. One way to help people accept a carbon tax is called revenue recycling. That means the government uses the tax money to help people. Scientific evidence has shown that, if the money is spent in smart ways—like helping schools or families—more people agree with the tax. This article looks at how using carbon tax money wisely can help stop pollution and make big changes for the climate.

CARBON

short expression for greenhouse gas emissions that cause climate change.

CARBON TAX

Policy that makes companies and people pay for their greenhouse gas emissions and pollution.

REVENUE

Funds received from companies and people paying for carbon tax.

REVENUE RECYCLING

Different ways governments spend carbon tax revenue.

A QUICK STORY WITH A HAPPY ENDING

Climate change has already had some serious effects on people's lives, and it is getting worse because we are not doing enough to stop it or even limit its impact. Why do people not simply act together powerfully to stop climate change? How can we make politicians, companies, and communities around the world interested in climate action? Here is a short story that describes one idea:

Imagine a town with lots of big cars that puff out dirty air. The dirt is made of **carbon**. So, the town makes a rule: every day that you pollute, you must put 25 cents into a special box. This quarter is called a **carbon tax**. The money in the box is called **revenue**, which means money that is earned. The town decides to reuse the revenue to help the community—this is called **revenue recycling**. Every month, they open the box and use the money to build parks, pay for school lunches, or help families heat their homes in winter. Each year, the town makes a new plan for how much to pay into the box and how to spend the money. Soon, the air gets cleaner. People want to pollute less and save their quarters. And the town has greener parks, warmer homes, and happier kids.

The following graph (Figure 1) gives you an overview of how carbon tax revenue recycling works.

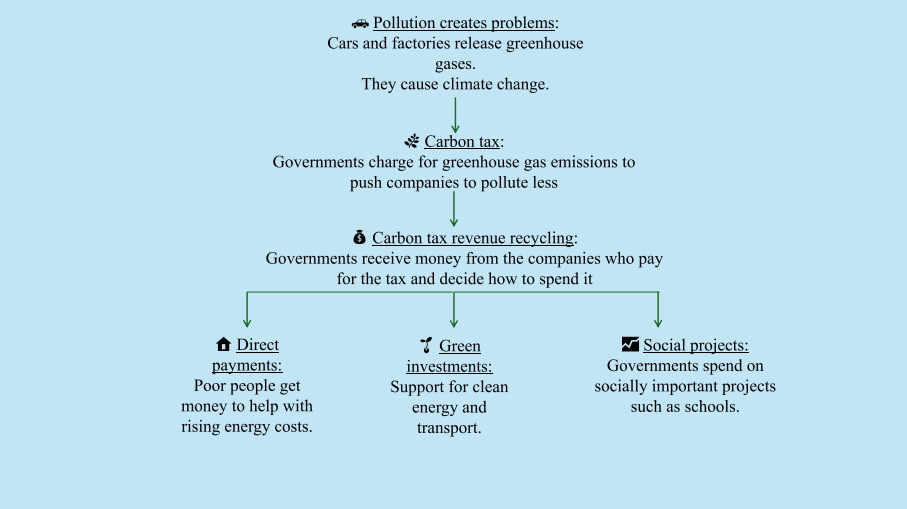

Figure 1

How carbon tax and revenue recycling work.

So now you know WHAT carbon tax is and WHY it might help society and the environment. Let's dive into the science behind it, how it works and how it could work better!

THE CHALLENGE OF A TAX ON CARBON

POLICIES

Governments' plans to solve important issues.

SUSTAINABLE ENERGY

Energy that will not run out and does not harm the environment.

CARBON PRICE

Level of carbon tax which determines how much money people have to pay for pollution.

Scientists have been saying for a long time that carbon taxes are the best way to tackle climate change. Some climate **policies** make people pay for the greenhouse gas pollution caused by their factories, cars, buses, airplanes, and air conditioners. But this carbon tax is expensive for some people. The idea behind charging a carbon tax is that people will want to avoid paying it, so they will switch to using things that do not burn fossil fuels or cause pollution. Non-polluting things use **sustainable energy**—energy that will not run out and does not harm the environment—like solar-powered lights and electric buses.

The problem is, even though the carbon tax can lead to good things, many people think paying *any* tax for pollution is unfair. And, if the amount of the tax, called the **carbon price**, is unpopular, politicians who support it may not get elected. If they do not get elected, they cannot take any climate action. Let us look at why carbon taxes may seem unfair.

First, poor people struggle harder to pay for transportation and for heating and cooling their homes than rich people do. A carbon tax makes their energy and transportation bills even higher. Telling them, "It is to help the environment", may not be enough. "How will it help us?" they might ask (Do not worry, we will get to that).

Or they might say, "We do not believe that paying more for something will make people use less of it, or switch to a non-polluting product". For example, many people like to keep their homes warm in winter or need their cars to go to work. So, even if their energy bills or the cost of gasoline goes up, they may not change their habits or reduce how much they use. This is true in some cases.

Because of these problems, the government keeps the tax too low to do all the great things it could do. But do not worry, because even at these low carbon prices, there is now plenty of evidence that carbon pricing is effective in reducing greenhouse gasses, and it *does* make some people and companies change their behavior or switch to products that use sustainable energy [1]. For example, since the carbon tax began in the European Union, people have been using less polluting coal to heat their homes and for electricity. And they use more renewable energy sources, like solar and wind power. The question is, how can we improve climate policies so that more people accept and support them?

WAYS TO WIN SUPPORT FOR CARBON TAX

There are several ways to improve the acceptance of climate policies like the carbon tax. First, politicians and scientists must educate the public more about how taxing carbon to reduce pollution can

help our environment—cleaner air, fewer terrible storms, and saving natural resources, like clean water. In addition to educating people about this urgent issue, we need to recycle the tax revenue. As you learned in the story, revenue recycling means taking the money that governments collect in carbon taxes and giving it back to the people! The tax may not seem unfair if it is used to help poor households pay for heating their homes or for gasoline to drive their kids to school [2]. Going further, carbon tax money can be used to pay for eco-friendly products and projects, like putting solar panels on the roofs of homes and companies. Projects like these make energy cheaper and cleaner for everyone, proving that climate policies are good for the environment and for people's wallets.

There is more. If people are aware of serious problems in their society, such as poor education or health care, the government can promise to spend the carbon tax revenue they will collect that year helping those areas. Who would complain about better schools and hospitals?

Table 1 shows how some countries use the carbon tax revenue in socially and environmentally helpful ways.

Table 1

Some great things that **revenue recycling** does for countries.

Country	What the money is used for
Ireland	Supporting eco-friendly changes for farmers and families, and helping poor people
Colombia	Working toward peace by paying for environmental projects
Portugal	Reducing taxes for big families and supporting forest-growing projects
China	General budget: the money is used for many different projects
Luxembourg	Climate action programs and helping families by lowering taxes
Switzerland	Reducing health insurance costs and supporting eco-friendly buildings,

Source: Muth [3] and World Bank.

Table 1

MY RESEARCH ON CARBON TAXES

When more people see positive results, they begin to support carbon taxes, and politicians are more likely to create policies that include higher carbon prices. The higher the price, the more revenue they will receive to protect the environment.

Of course, countries are all very different from each other, so the same revenue recycling plans will not work everywhere. In some countries, where there are more poor people, governments need to spend money helping people afford the higher price of the carbon tax. Other countries face bigger threats from climate change, such as rising sea levels that can flood their streets and cities. In these countries, the

revenue can help them prepare for climate change, like building sea walls to protect communities from the rising ocean.

To figure out which revenue recycling methods will work best, we need to look at the specific situation in each country. We need to understand how much business the country does, how much pollution the country makes, and how much of the population is rich vs. poor. Then policies can be designed to help each situation.

My research looks at three main ways of using the money from a carbon tax: (1) helping poor people or people who live far from cities; (2) working on projects that help the environment; and (3) spending revenue on important social causes, like education. The idea is that, if people's needs are taken care of, they will be willing to pay more for the pollution they make.

THE BIG RESULT: HELPING ENVIRONMENT AND SOCIETY TOGETHER

One of the most important things my research shows is that, in richer countries with better education and technology, people are generally willing to pay higher taxes even if the revenue is not used to help the community. But in many countries that cannot survive without their polluting factories and transportation, or countries that have many poor people, politicians should use the tax revenue to help the people. If the money can both help the poor and also pay for eco-friendly projects, then people are even more willing to pay higher carbon prices.

I also hope the people in government can use what I have learned through my research to make better rules and smarter choices. How can they do that? By spending the money from carbon taxes wisely!

But to spend wisely, they have to know what people really need. Think about your parents—they try to find out what you need for school, or what you might want for your birthday. Sometimes they even ask you. Politicians should be like that too. They should listen to the public—and that includes kids!

You may not be able to vote yet, but you can still help change minds—including the minds of politicians. When grownups and kids speak up, ask questions, and share what they have learned, leaders start to pay attention. As more people understand why carbon taxes matter, they will support politicians who take real action to protect our planet.

ORIGINAL SOURCE ARTICLE

Muth, D. 2023. Pathways to stringent carbon pricing: configurations of political economy conditions and revenue recycling strategies. A comparison of thirty national level policies. *Ecol. Econ.* 214:107995. doi: 10.1016/j.ecolecon.2023.107995

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YOUNG REVIEWERS

SIDDHANT, AGE: 12
Hello friends, I am Siddhant, and I am 12 years old. I am enthusiastic about exploring earth's evolution, from the time of dinosaurs to the present. I love connecting with nature and its creatures, reading books, watching documentaries, and sketching from my imagination. I find travelling to be fun and always excited to

visit new places. I love solving abacus, and my favorite subjects are science, English, and mathematics.

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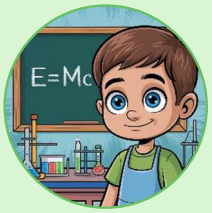
I am Tahmid and I am a big fan computer games. I love coding and making new friends in my virtual sports community. I also love music and spend a lot of time playing my guitar. My hobby is gardening and I love to germinate any seed I find. I wish one day I will be a great **plant** scientist.

TAHIYAT, AGE: 11

My name is Tahiyat and I am 11 years old. I love drawing, painting and making paper crafts. I enjoy much watching craftsman and "Origami" in youtube. My aim in life is to be a good doctor. In free time I love to sing and dance. My favorite cartoon character is Dipper, Mabel, and Grunkle Stan from **Gravity Falls.**



TANVIR, AGE: 14

I am Tanvir. I love science and reading story books. Specially the universe, star, galaxy and science experiment attract me so much. My favorite TV show is **Brainchild** – A fun, science-based show answering cool kid-friendly questions.

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Daniel Muth is a research associate at Vrije Universiteit Amsterdam. He just finished his Ph.D. in public policy at Central European University, Vienna. His earlier research focused on global carbon pricing and climate policy development in Central Europe. Currently, he is working on a project funded by the European Union called NAVIGATOR. The NAVIGATOR project was created to advise the European Union as it "navigates" (sails through) the complicated ocean of climate governance. Climate governance is how countries, communities, businesses, and people work together to make rules and policies to help protect the Earth. The EU takes a leading role in this complex task.*d.muth@vu.nl

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EARTH SCIENCES
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WATER FLOWS DOWNHILL: HOW LOOKING "UPSTREAM" CAN HELP MAINTAIN A HEALTHY SEA

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YOUNG REVIEWERS:

AYAT
AGE: 12

Our planet is in trouble. We are losing plants, animals, and habitats, and the processes that link them are changing. Nature is becoming sick. People have been trying to fix this problem, but the situation keeps getting worse. One problem is people ignore a simple law of

GERMOGLI-AMO

AGES: 9–10

nature—ecosystems are connected. For example, when forests are cut down, soil is exposed to rainfall and washed into the sea, where it covers and kills shellfish. We made a computer model to explore what happens when the people making the rules on land are slow to respond to problems in the sea. We found that paying attention to the natural land-to-sea connections can help save all ecosystems from sickness. Our computer model demonstrates to governments that a major solution to environmental crises is to realize the connections between ecosystems, and talk and work with each other. Our job is to make them listen!

PEOPLE ARE NOT HELPING ECOSYSTEMS QUICKLY ENOUGH!

You have probably heard about the multiple crises the planet and humanity are facing, from a warming climate to the widespread loss of species. It sounds grim, but there are solutions! First, we need to understand the problems that we might encounter on the path to finding those solutions.

The **biodiversity** crisis—the loss of many of the unique forms of life on Earth—is one of the biggest problems humanity faces. Since humans started roaming the Earth, half of all natural forests and most species of wildlife have been lost [1, 2]. This loss is a massive problem because it puts **ecosystems** out of balance, making them vulnerable to collapse and threatening our existence. This crisis is not just about the loss of forests and large animals. All forms of life have important roles to play in our planet's life-support system, contributing to our food, water, and the air we breathe.

But humans are smart, right? And we know a lot about the causes of the biodiversity crisis. So why are we not doing more to stop it? The good thing is that people everywhere are working to solve this problem, and **conservation** is helping protect ecosystems from further damage. The problem is that our progress is too slow. To find a solution and speed up our progress restoring ecosystems, we first need to figure out why people's reactions to environmental problems are so slow.

BIODIVERSITY

The variety of life on Earth. Biodiversity can be the variety of animals, plants, fungi, microbes, and habitats. High biodiversity is generally considered important for the function of the Earth.

ECOSYSTEM

An area where both living (plants, animals, microbes) and non-living elements (weather, rocks, sand, water, natural chemicals) work together and interact in balance to form a unique bubble of life.

CONSERVATION

The practice of protecting the natural environment from negative impacts of human activities.

WHY ARE PEOPLE SLOW TO PROTECT AND RESTORE ECOSYSTEMS?

One of the reasons people are slow to act is because people do not talk to each other. This might sound too simple, but it is true—people in charge tend to focus on only one problem at a time rather than looking for ways to solve many problems together. For example, in most countries there are separate departments in government,

with different people writing different rulebooks (called policies) for things like building cities, cutting down forests, and catching fish from the sea. Then there are other departments writing policies about protecting ecosystems. These are all busy people, so they do not talk to each other often enough—and this can create confusing policies.

Different rules for different places, activities, or ecosystems make it hard to make fair decisions for everyone and to protect ecosystems. This is a problem because the plants and animals on land, in streams and lakes, and in the sea are all connected. If people do not talk about all the connections, they might make decisions that have bad consequences elsewhere on the planet.

LAND, FRESHWATER, AND SEA ARE CONNECTED

Ecosystem connections are a natural part of the balance of life on Earth. For example, fish such as salmon migrate from streams out to sea, where they feed and get lots of nutrients for their journey back upstream, where they breed and release their eggs (Figure 1A). On their way upstream, some salmon get eaten by bears (Figure 1B), who poo in the forests and fertilize the trees with the nutrients that the fish brought from the sea [3]! In island ecosystems, seabirds provide the same **"Nature's contribution to people"** (sometimes also called "ecosystem services"). These connections between ecosystems can be found everywhere, and they often involve the movement of plants, animals, nutrients, and other forms of energy.

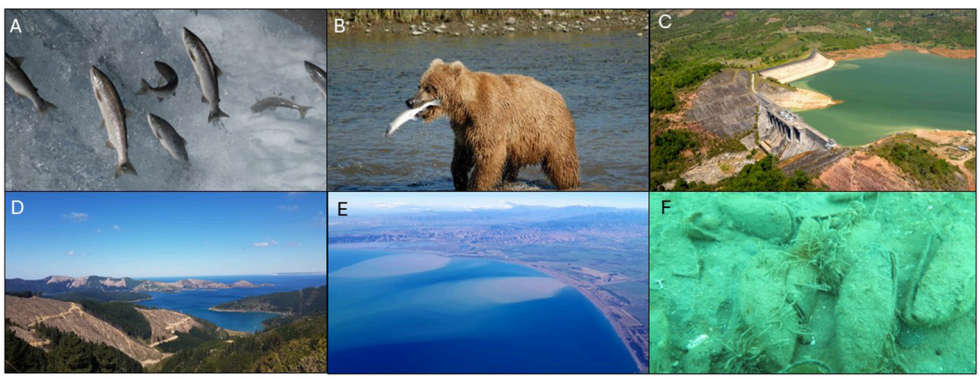

Figure 1

Bears pooping in the woods are just one example—many connections are critical for the Earth to function and support life. However, these connections also mean that when we damage one ecosystem, it has consequences for other ecosystems. For example, when we build a dam to store water (Figure 1C), we can block fish from migrating and providing food for the bears and nutrients for the forest. Building that dam removes a major food source for the bears upstream! When we

"NATURE'S CONTRIBUTIONS TO PEOPLE"

All the ways that nature can benefit people's quality of life. Examples include providing food and water, and regulating environmental conditions like reducing flooding risks.

Figure 1

(A) Salmon migrate from the sea upstream. **(B)** Those salmon provide food for bears in the rivers. **(C)** Building dams stops this important connection. **(D)** Cutting down forests exposes large, bare patches of soil, like on the hillsides in this photo. **(E)** This soil is washed by the rain into rivers and out to sea. **(F)** The soil eventually settles to the seafloor and smothers shellfish species living there, like mussels. (Photo credits: **(A)** Russ Taylor, NPS, PDM 1.0 via Flickr; **(B)** Carl Chapman, USA, CC2.0 via Wikimedia; **(C)** Quang Nguyen Vinh via pexels; **(D)** R. Gladstone-Gallagher; **(E)** C. Cornelison; **(F)** J. Hillman)

cut down forests, large areas of bare soil are exposed (Figure 1D). When it rains, that soil gets washed into the rivers and out to sea (Figure 1E), smothering and killing the shellfish (like mussels) on the seafloor (Figure 1F) [4]. Thus, when we cut down trees, it can destroy the homes of forest animals (like bears) and animals downstream (like mussels living in the ocean).

You are probably starting to see the problem emerging—people make decisions "upstream" without thinking about the consequences for the people and ecosystems "downstream", like the shellfish in the ocean. On the other hand, people "downstream" make decisions without thinking about the consequences "upstream", like the bears living upstream of the dam.

WE NEED TO RESPECT THE CONNECTIONS!

We wanted to find out what happens to ecosystems when people do not look downstream before they make the rules and decisions. We made a **computer model** to explore the consequences for an ecosystem in the sea, depending on the upstream activities on land and how fast people react to environmental change. In our computer model we tested three cases, but we will just talk about two of them here.

COMPUTER MODEL

A computer program that simulates how parts of a system—like plants, water, and weather—interact, helping scientists explore what might happens when something changes.

TIPPING POINT

When a small environmental change results in a large reduction in the health of the ecosystem, from which it is difficult to recover.

In the first case, the people making policies on land were not the same people suffering the consequences downstream (e.g., the people who had fewer fish to catch or no clean beaches to swim at) (Figure 2A). This slows the action to help the downstream ecosystem, which can cause the ecosystem to reach its **tipping point**. Tipping points occur when small changes have big consequences. Think about kicking a ball up a hill. It takes lots of effort to kick it to the top of the hill, but once you get to the top of the hill, you only need one little kick over the top, and it will start rolling down the other side of the hill on its own. Once the ball is rolling down the hill, it gets faster, and it is hard to catch up to stop it. Tipping points in ecosystems are similar, but the consequence is rapid damage to the ecosystem (To learn more about tipping points, see this Frontiers for Young Minds article). It is difficult for us to catch up and reverse the ecosystem damage once it has started, and the ecosystem may never recover. Our model showed that tipping points can occur when people do not talk to each other and when they are slow to act.

In the second case, actions to protect the ecosystem are faster because everyone works together and recognizes that land, freshwater, and sea ecosystems are connected—ensuring healthy ecosystems for everyone (Figure 2B). This means that the people who are in charge of the policies for activities on land not only talk to the people who live and work on land, but also to those who live and work along the streams and in the sea. The people making the policies for the people

Figure 2

Can you spot the differences between **(A)** and **(B)**? **(A)** Here, the people making decisions may not talk to the people who suffer the consequences of the decisions. **(B)** Here, people are working together. More land is set aside for native trees and there is less impact from human activities like deforestation, farming, and factories. This means less pollution and erosion of soil into the water, so aquatic ecosystems are clean and have more fish. Some fish can migrate, maintaining healthy connections across land, freshwater, and sea. More people are enjoying the environment.

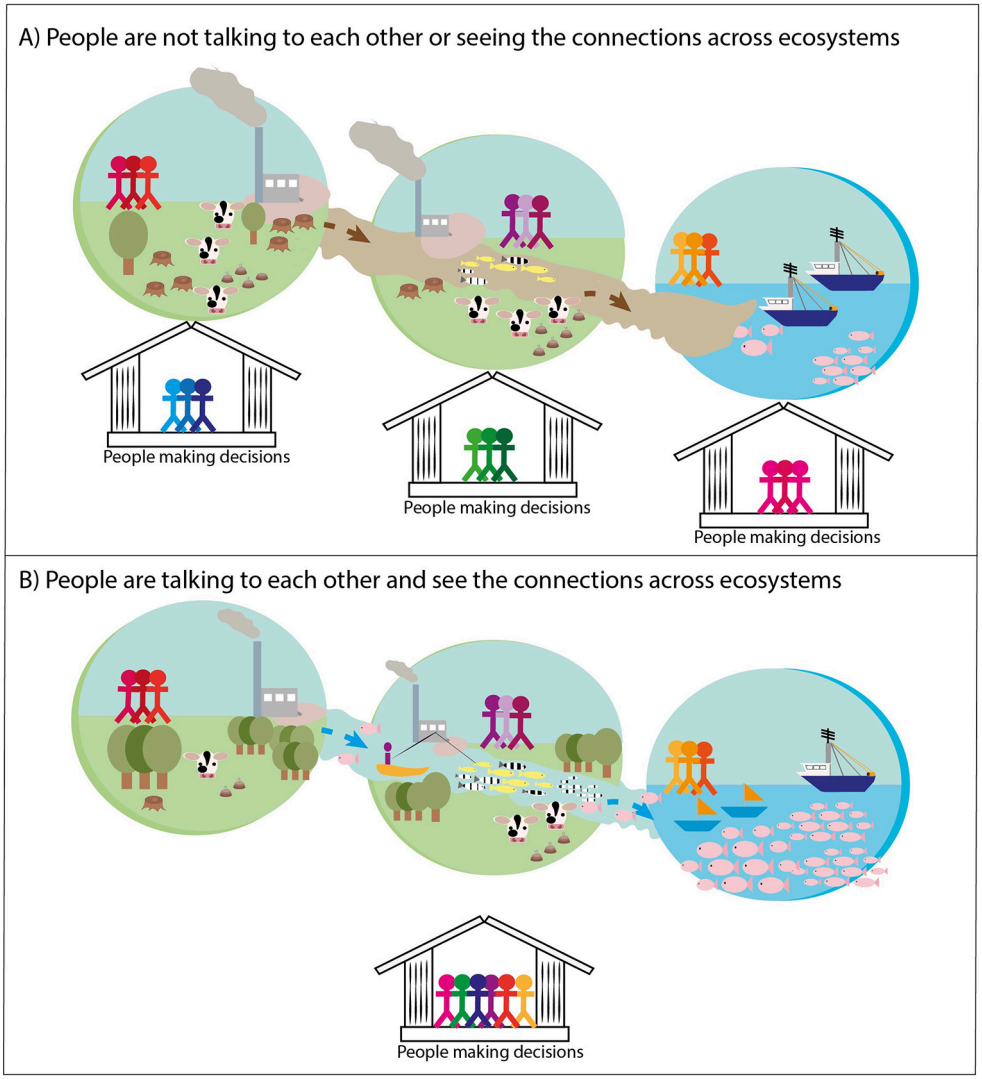

Figure 2

fishing in the sea talk to the people making the policies for activities on land.

"Nature's contributions to people" (e.g., food, clean water, clean air to breathe) can be lost if tipping points are reached (like in Figure 2A) [5]. This happens because, for example, the people benefitting from cutting down forests are separated from and do not see the consequences for people downstream, who rely on shellfish for food. These types of consequences are often felt by **Indigenous people** and less privileged people, leading to an unequal society. Other activities that can have negative consequences for connected ecosystems and "Nature's contribution to people" are pollution and plastic litter from towns and cities, factories and farms, and too much fishing or hunting.

INDIGENOUS PEOPLE

Ethnic groups whose ancestors lived on and had connections with the lands, natural resources, and ecosystems of a place and consider themselves distinct from other people occupying the area.

WORKING TOGETHER WITH NATURE TO PROTECT ECOSYSTEMS

Our research shows that we need to work with nature by taking notice of the "good" connections (e.g., migrating fish) and the "bad" connections (e.g., flow of pollutants) between land, freshwater, and sea. We need to show the governments who make policies, and the local/regional people (who make individual decisions based on those policies) that ecosystems are connected and that working together across land, freshwater, and sea will result in faster actions and a healthier environment. To work together, we will need to encourage a new culture for people who make the rules, people who are doing the activities (e.g., building cities and harvesting forests), and people who suffer the consequences of other people's activities in the environment. We need more research that connects land, freshwater, and sea ecosystem science with **social sciences** (science about people and how they behave). For centuries, Indigenous people worldwide have been guardians of the natural world, understanding connections between ecosystems. To protect Earth's ecosystems and connections for future generations we need to get better at combining science, Indigenous knowledge and people's values and behaviors so that we can improve the way we manage the environment.

SOCIAL SCIENCES

The scientific study of human society, behaviors, and relationships.

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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

AYAT, AGE: 12

I am a 12-year-old with a big passion for sketching and painting, especially when nature sparks my creativity. My favorite books, like "Amari" and "The Magicians of Paris", along with other fantasy stories, fuel my imagination. I love cycling, playing chess and badminton, and hiking to uncover nature's hidden treasures. Along the way, I enjoy taking notes and drawing detailed sketches of the plants and animals I encounter!

GERMOGLIAMO, AGES: 9–10

The Sprouts group of Young Reviewers is composed byEdoardo, Ilyan, Yuri, Flavio, Ernesto, and Lorenzoand Mattia. They attend their 4th-5th year at the primary outdoor parental school GermogliAmo in Colonna (nearby Rome, Italy).

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Rebecca V. Gladstone-Gallagher is a senior lecturer at the University of Auckland in Aotearoa New Zealand. She is a marine scientist and is fascinated by the way marine animals, plants, and environments all work together to make a functioning ecosystem. These connections and interactions are important to understand how marine ecosystems respond to human activities. Her research informs actions that protect and restore marine ecosystems. *rebecca.gladstone-gallagher@auckland.ac.nz

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Johanna Yletyinen is a senior researcher at the University of Jyväskylä, Finland. She investigates the resilience and sustainability of natural resource systems, such as fisheries and forests. She often uses modeling to better understand the complex interactions between people and the environment. Her work aims to find solutions for improving the wellbeing of both people and the environment.

VASILIS DAKOS

Vasilis Dakos is a researcher at Université de Montpellier in France. He is interested in how ecosystems can be resilient to global changes and what causes tipping points. He uses models to identify early-warning signals of tipping points.

EMILY J. DOUGLAS

Emily Douglas is a marine ecologist at the National Institute of Water and Atmosphere (NIWA) in Aotearoa New Zealand. Her research focuses on coastal seafloor ecosystems, and how those ecosystems change with climate change and other human-made stressors. She uses field experiments and modeling to investigate what happens to ecosystem functioning and biodiversity when stressors like heatwaves and nutrient pollution occur.

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JUDI E. HEWITT

Judi Hewitt is a professor of statistics at the University of Auckland, Aotearoa New Zealand. She applies statistics to data collected in marine ecosystems to identify patterns between marine species and environmental change. She is particularly interested in how those patterns can help us manage marine ecosystems to prevent further degradation.

DANIEL HIKUROA

Daniel Hikuroa (Ngāti Maniapoto, Waikato-Tainui, Ngaati Whanaunga) is an associate professor at Waipapa Taumata Rau the University of Auckland in Aotearoa New Zealand. Dan is a geologist and an established world expert on weaving Indigenous knowledge and science to realize the dreams of the communities he works with.

STEVEN J. LADE

Dr. Steven Lade is an Australian Research Council Future Fellow at the Australian National University. His research focuses on how ecological systems including humans and nature can be resilient. He uses mathematical models to explore how ecosystems and the planet change with things like climate change.

RICHARD LE HERON

Richard Le Heron is emeritus professor of geography at University of Auckland in Aotearoa New Zealand. As a teenager he witnessed depletion of flatfish at local beaches, wetland drainage for farming, and run-off from agricultural and industrial facilities into rivers. These experiences inspired him to study geography, economics, and zoology. His research focuses on human behaviors and how they influence investment and regulation.

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Alf Norkko is professor at the University of Helsinki in Finland. He works with marine ecosystems, and his research focuses on understanding how biodiversity and climate change work together in affecting coastal ecosystems.

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George Perry is a professor at the University of Auckland in Aotearoa New Zealand and works on understanding the effects of humans on forest ecosystems. George is particularly interested in how human-caused changes, especially fire, have changed forest ecosystems and how those changes are challenging for restoration and conservation in modern ecosystems. He is also interested in how animals and plants interact through seed dispersal.

CONRAD A. PILDITCH

Conrad Pilditch is a professor in marine science at University of Auckland in Aotearoa New Zealand. His research focuses on marine soft sediment ecosystems, one of the most extensive habitats on the planet. He explores how these ecosystems are impacted by human activities and climate change. Conrad and his team of students and collaborators have generated new knowledge that underpins better environmental management.

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David Schiel is a distinguished professor in marine science at the University of Canterbury and adjunct professor at the University of Waikato Coastal Lab, in Aotearoa New Zealand. His research focuses on kelp forests. He and his colleagues investigate how heat waves and land-based stressors (such as sediment runoff) change kelp forests. He collaborates closely with Māori partners and environmental management agencies to improve marine ecosystem health and outcomes.

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Dr. Ewa Siwicka has over 10 years of experience exploring how nature contributes to human wellbeing. Ewa's mission is to make nature restoration an integral part of the economy. Ewa's work helps businesses and organizations navigate their transition toward nature-positive.

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Dr. Helen Warburton is a freshwater ecologist and senior lecturer at the University of Canterbury in Aotearoa New Zealand. Her research explores the interactions between different species in streams and rivers, and aims to improve biodiversity outcomes and guide effective restoration efforts.

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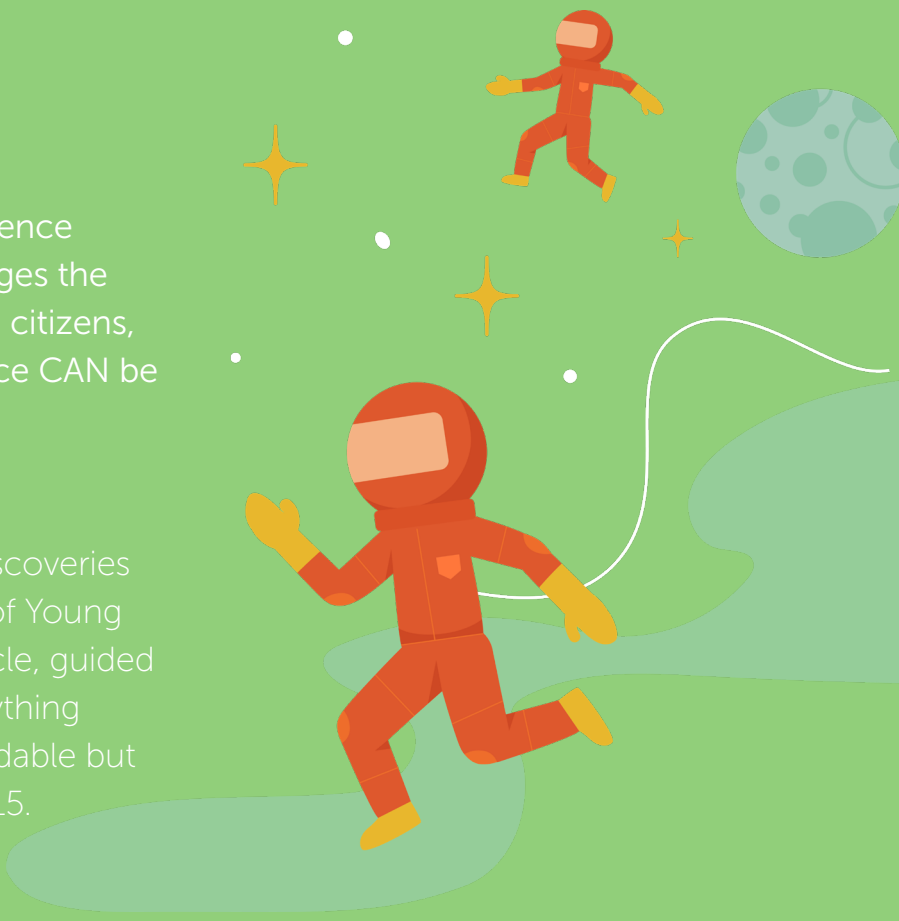

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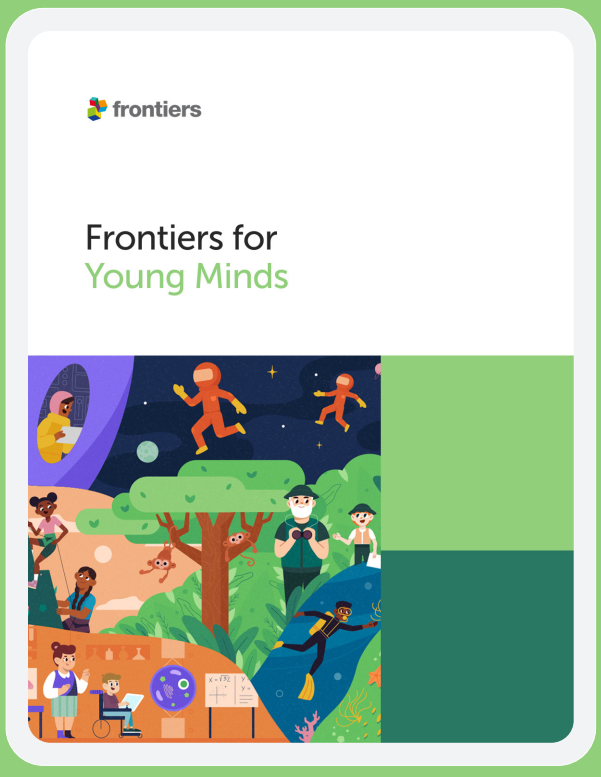

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