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BIODIVERSITY
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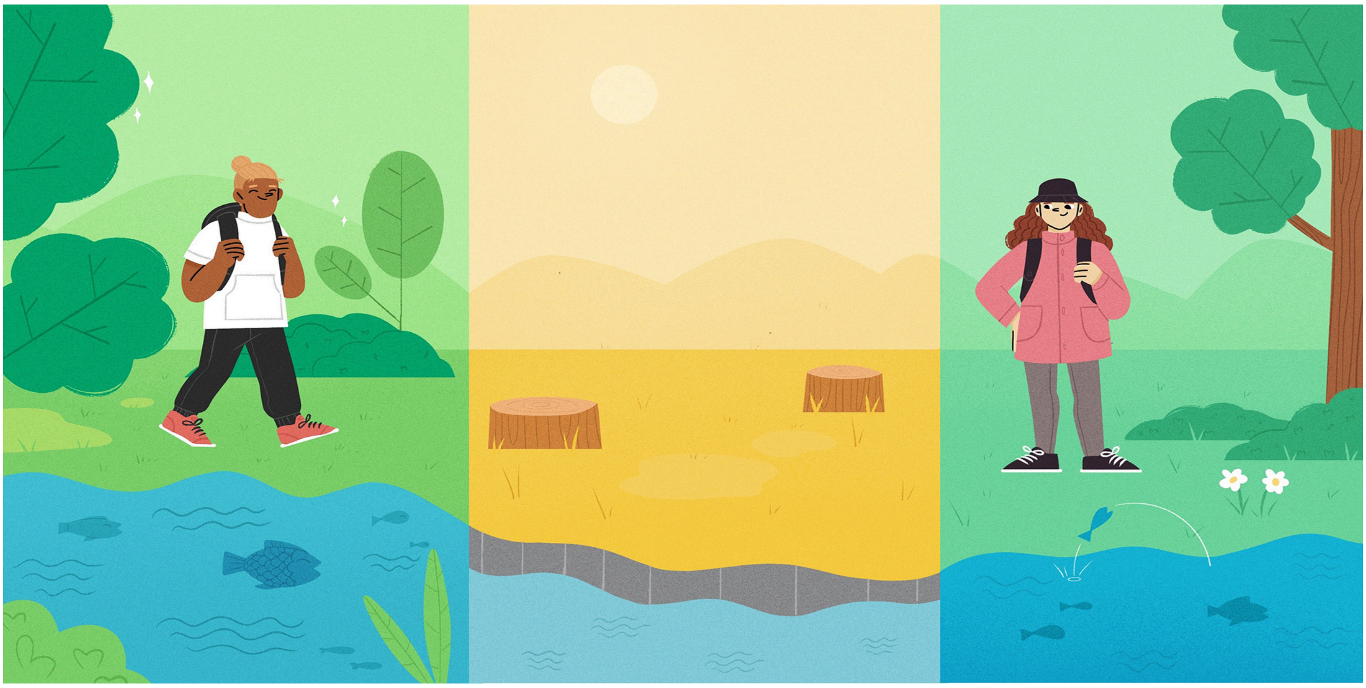

SOLVING THE PUZZLE OF ECOSYSTEM RECOVERY

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YOUNG REVIEWERS:

ALMA
AGE: 11

BATOUL
AGE: 9

Human activities, past and present, have a big impact on nature, affecting ecosystems in profound ways. Scientists are working hard to figure out the best methods to restore damaged ecosystems. But ecosystem restoration often does not go as planned, resulting in very different ecosystems than before. For example, some animals that used to live in an ecosystem can take a long time to return or do not come back at all. To understand the complexities of

JOSEPHINE

AGE: 12

TAMMAM

AGE: 14

ecosystem recovery, scientists have come up with a theory called the asymmetric response concept (ARC), to understand how ecosystems recover. The ARC helps us describe the various responses that can happen after ecosystem damage and why the responses happen that way. Once we understand these responses, we can help ecosystems become healthy again. By learning how organisms rejoin damaged ecosystems, we can better protect our environment for the future.

WHAT ARE STRESSORS?

On our planet, we live together with many types of organisms: animals, plants, and even very small organisms like fungi or bacteria. A group of organisms living in the same area forms what is called a community. A community interacts with its environment for food and shelter. Together, the community and its environment make up an ecosystem. A coral reef, a forest, and a river are all examples of ecosystems. Organisms within an ecosystem depend on each other and on their habitat. Let us look at the example of a river: in this freshwater ecosystem, shrimp provide food for fish. The same shrimp shred the leaves that fall into the river, converting them into smaller pieces and releasing nutrients that are needed for algae to grow. Algae provide food for river snails, which can also be eaten by fish. Bacteria and fungi act like a clean-up crew, taking care of all the leftovers. These organisms all play important roles in keeping the water clean and helping the river to stay healthy (Figure 1A). All parts of an ecosystem are connected and in a dynamic balance with each other, fitting together like pieces of a living puzzle.

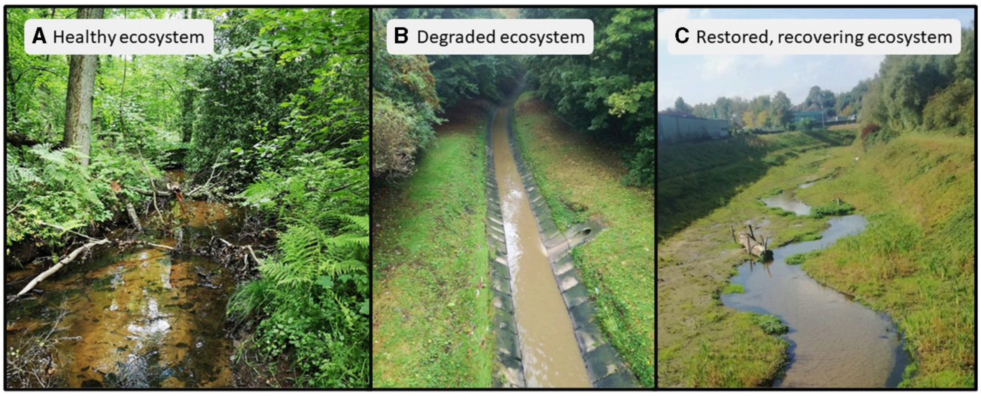

Figure 1

Figure 1

Three rivers in Germany as examples of what healthy, degraded, and recovering ecosystem look like. **(A)** A near-natural, healthy part of a river, where lots of different species can live. **(B)** A channeled, degraded river section, where habitat has been damaged and many organisms can no longer happily live. The river bottom has been turned to concrete, and wastewater flows into the river, turning it brown. **(C)** A restored and recovering section of a river, where some of the original habitat is back and some original species can live again.

Humans take part in river ecosystems too, but many human activities are harmful to rivers. Humans can destroy river habitats by building dams that block the flow of water, turning riverbeds into concrete channels, overfishing, or polluting the water with chemicals and trash. These disturbances happen along with natural events like storms,

STRESSOR

Any factor that causes organisms, communities, or ecosystems to become damaged, such as chemicals, high temperatures, pollution, or habitat destruction.

DEGRADED

An of unhealthy, bad condition following damage. In nature, a degraded ecosystem is no longer a nice place for many organisms to live.

TRAJECTORY

The path an ecosystem takes, measured by how the community changes over time.

RESTORATION

The process of fixing something or making it new again. For ecosystems, this usually means cleaning up the habitat, removing stressors, and reintroducing species.

floods, and fires—events that natural communities are more adapted to. All these **stressors** make it hard for living organisms to survive and can damage their habitats, disrupting the balance that holds the ecosystem together and causing the ecosystem to become **degraded** (Figure 1B). Some stressors can be stronger than others and, in many instances, multiple natural and human-caused stressors occur at the same time [1].

CAN ECOSYSTEMS RECOVER?

The good news is that ecosystems can recover once stressors are removed. Healthy ecosystems are important for humans as well as for many other species, and many people have been working to restore degraded ecosystems (Figure 1C). Some recover quickly without any human help once the stressors are gone. This is the response scientists most hope for. However, other ecosystems do not recover as well [2]. Some take so many years to recover that it is hard to tell if they are recovering at all. The asymmetric response concept (ARC) is a description of the possible **trajectories** (paths) ecosystems can take to recovery and the mechanisms explaining each type of path. "Asymmetric" in this name means that the rate at which ecosystems recover can differ, to the point that some never reach full recovery without help. The ARC helps us find out which ecosystems need our help to recover and how much effort is needed to restore them.

ECOSYSTEM TRAJECTORIES

The ARC defines five ecosystem trajectories, which reflect the real-life results of **restoration** efforts (Figure 2) [3, 4]. The first two trajectories, called the rubber band model and the broken leg model, lead to complete recovery but differ in the amount of time it takes the ecosystem to get there. The others, the partial recovery, no recovery, and new state models, either recover partly or not at all, even after a long time.

For the rubber band and broken leg trajectories, communities recover completely but take different amounts of time to do so. If you pull on a rubber band, it immediately goes back to its original state after you release it. Similarly, in the rubber band trajectory, any species lost from the community can return shortly after the stressor is gone. On the other hand, if you break your leg, it takes much longer to heal. So, in the broken leg trajectory, species that are lost or reduced in number need more time to return to the community, compared to the time it took to lose them due to stress.

Sometimes full recovery is not possible, and communities can either be partially recovered, not recovered, or transformed into a new state. In the case of partial recovery, some of the lost species cannot

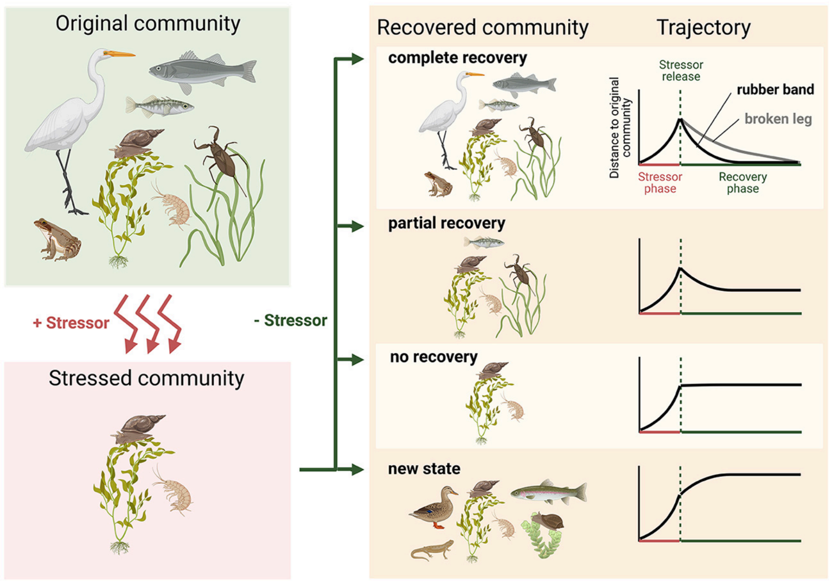

Figure 2

Figure 2

After stress, a community's recovery can be complete and fast (rubber band trajectory) or complete and slow (broken leg trajectory). In complete recovery, all the original species come back to the community eventually. Recovery can also be incomplete, which means that not all species come back to the community. No recovery means that the community remains the same as it was during the stress. Partial recovery means that some, but not all, species come back. In a new state, different species fill in the roles of the species that were there before (created with BioRender.com).

return to the community after the stress is gone. So, in the final community, one or more species are missing compared to the original community. For example, if our river had two fish species, only one might come back. In some cases, recovery is not possible at all, and the community remains in a degraded state, in which none of the lost species can return. In this case, no fish return to our river. Both partial recovery and no recovery are caused by changes in the balance of how species fit together in the degraded community. Among the puzzle pieces of ecosystem function, these changes involve relationships between two or more species, known as **biotic interactions**. Examples are relationships between predators and their prey and competition between organisms. Another possibility is that, after stress release, the community can transform into a new state, in which new species take the place of those from the original community. For example, a new type of fish could take the place of the fish that were in our river before the stressor, and a salamander might take the place of a frog.

BIOTIC INTERACTIONS

A relationship between two or more species in a community, such as predator-prey relationships, or competition between species for a resource.

ECOLOGICAL MECHANISMS SHAPE ECOSYSTEM TRAJECTORIES

As scientists, we want to find out which trajectory a degraded ecosystem will take once the stress disappears. To do so, we must understand what ecosystem responses occur during stress and how those responses change when the stress is gone. A community's recovery depends on how many organisms survive the stressful period. A species' ability to survive stress is known as its individual **tolerance**. For example, some frogs can freeze solid to survive cold winters, making them cold tolerant. Tolerance is most important *during* stress, and the individual tolerances of many species combined affect how

TOLERANCE

The ability to withstand environmental factors such as temperature or pollution. Sensitive species can only survive a small range of conditions, while tolerant species can survive in many different conditions.

the whole community changes under stress (Figure 3). A single species can also have different tolerances to different stresses—a very cold-tolerant frog can be very sensitive (intolerant) to chemicals in the water, for example. So, when there are multiple stressors at the same time, things can get complicated.

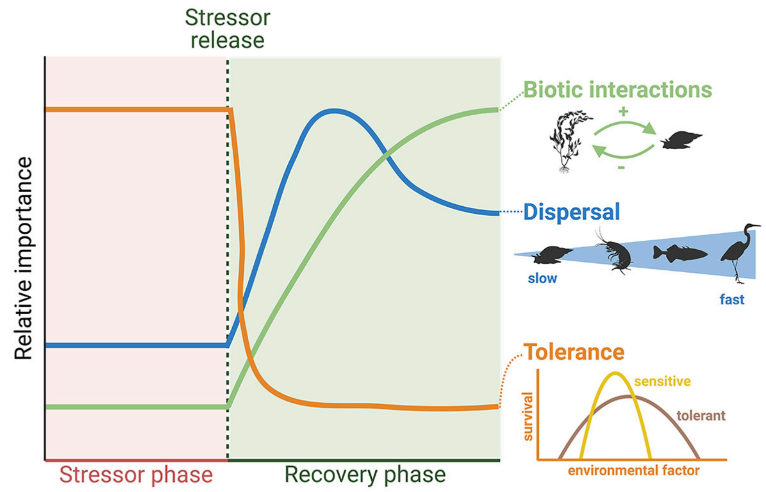

Figure 3

Figure 3

Tolerance, dispersal, and biotic interactions change in terms of how important they are after stressors are gone and the ecosystem recovers. During stress environmental factors, such as temperature or pollution, are out of the range that sensitive species can survive in. Tolerance is most important during stress, since only tolerant species can survive in the stressed ecosystem. Tolerance becomes less important during recovery, when less-tolerant organisms can survive in the ecosystem again. Biotic interactions and dispersal become more important during recovery. Dispersal determines how many and which species can come back to the ecosystem. Biotic interactions influence the conditions, such as food or competition, that allow the species that come back to stay in the ecosystem (created with BioRender.com).

DISPERSAL

The movement of species into or out of a habitat. Dispersal can be slow or fast.

Even if organisms are not tolerant, they can still come back to the damaged ecosystem once the stress is gone. The ability to move, known scientifically as **dispersal**, can help organisms escape a stressor and come back when the stressor is released. For some species, coming back will be easy—for example, if they did not move very far away or if they are really good at flying long distances. For others, coming back to a recovering ecosystem is more difficult. Think about a tiny river snail trying to move upriver compared to a fish that can swim quickly, for example.

Even if an organism makes it back to the recovering ecosystem, the organism might not remain there because the ecosystem may have changed during the stress. If a fish that eats shrimp travels back to a recovering location where all shrimp have died, the fish will have nothing to eat and cannot survive there. This relationship between a predator and its prey is an example of a biotic interaction. These interactions are really important for ecosystems to function, but they can also prevent species from returning and prevent the ecosystem from recovering completely. Biotic interactions and dispersal are extremely important during recovery (Figure 3).

The combination of the tolerance of organisms, their dispersal, and the biotic interactions between them determines how many organisms die or leave during stress, and which ones can come back once the stress is gone. An ecosystem with many tolerant organisms and organisms that can disperse easily yet remain nearby (or can easily return) will be more likely to follow the rubber band trajectory of recovery. If many organisms are sensitive and all the food sources for important predators disappear, the ecosystem may not recover at all. If some species have high dispersal and others do not, partial recovery can occur, as only some animals will come back. A degraded community may also be invaded by new species that can deal better with the new balance of biotic interactions in the degraded ecosystem. Knowing which trajectory a stressed ecosystem will follow and which mechanisms lead to that trajectory helps scientists and ecosystem managers to create a plan of action to put the ecosystem on the path to recovery.

HOW CAN THE ARC BE USED?

With the asymmetric response concept, scientists can understand how the mechanisms of individual tolerance, dispersal, and biotic interactions work together to affect the trajectory of the ecosystem they are restoring. When they understand the trajectory an ecosystem will follow, they can give this information to ecosystem managers who take action to help return the ecosystem to a healthy state. Ecosystem managers include people working at water companies; natural parks; and city, state, and county governments, who make rules on how land and water are used. For ecosystems that follow the rubber band trajectory, nothing extra is needed. But for ecosystems that have no recovery, action is needed to avoid mistakes of the past. Are there not enough organisms living nearby? Managers can re-introduce them. Did the food source of a predator disappear? Managers can make sure the food source is back before re-introducing the predator. Once ecosystem managers know which conditions lead to no recovery, they can take steps to make sure those conditions do not happen again. Together, scientists and managers can use the ARC to restore more degraded ecosystems back to a healthy and happy state.

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ORIGINAL SOURCE ARTICLE

Vos, M., Hering, D., Gessner, M. O., Leese, F., Schäfer, R. B., Tollrian, R, et al. 2023. The Asymmetric Response Concept explains ecological consequences of multiple stressor exposure and release. *Sci. Tot. Environ.* 872:162196. doi: 10.1016/j.scitotenv.2023.162196

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YOUNG REVIEWERS

ALMA, AGE: 11

Welcome ! I am Alma. I like mathematics and science, especially biology. Last year, I took a robotics course, and it was very helpful to me. I hope to get into medical school. My hobbies are drawing and coloring. I am a highly creative person with an inquisitive mind. Also, I am a social person who enjoys new experiences. I am making amazing things out of Legos. I have a pet, which is a cat, which I love. I play with her a lot.

BATOUL, AGE: 9

Hi. I am Batoul, and I am 9 years old. My favorite color is purple. My favorite fruit is watermelon. I enjoy reading. Basketball and swimming are two of my favorite hobbies. Mathematics and science are my favorite subjects because they allow me to try new things and participate in argumentative discussions. At school, I am a member of a group that works to protect the environment.

JOSEPHINE, AGE: 12

My name is Josephine, I am 12 years old. I live with my mom and dad, my four parakeets and a husky. My favorite color is neon-orange, I figure skate, swim and play golf. I like to read and watch shows about animals, dragons and mythology. I love animals, but I do not have a favorite since all have different skills and features. I enjoyed working on the article and I hope to do another one.

TAMMAM, AGE: 14

Hello, my name is Tammam. I am 14 years old. My hobbies are playing padel and tennis. I enjoy reading and asking questions to improve my knowledge. Also, I like biology and medicine, so I aspire to be a great doctor in the future. I am looking forward to increasing my knowledge of health science. My favorite pieces of equipment are the microscope and the telescope.

AUTHORS

HELENA S. BAYAT

I am an ecotoxicologist working on understanding how organisms cope with multiple stressors in our changing environment. Multiple stressors include chemicals like pesticides as well as environmental conditions like heat waves and droughts. My Ph.D. research focuses on finding out the tolerances to salt and heat for freshwater organisms, and using these tolerances to find out how whole communities change in rivers under heat and salt stress. By figuring out how organisms and whole communities react to stress, my research aims to support actions to protect and restore our freshwater ecosystems. *bayat@uni-landau.de

JULIAN ENß

As an ecologist and entomologist, I explore nature like a detective, studying where animals live and how they interact. Currently, my Ph.D. project focuses on insects with a unique lifecycle—from river-dwelling larvae to flying adults like caddisflies, mayflies, and stoneflies. I am uncovering their secrets, including how far they can fly and how many take to the skies. This knowledge is vital for ecosystem recovery. To become an ecologist or entomologist, you can explore your surroundings, observe insects, and ask questions about nature's workings.

CAMILO ESCOBAR-SIERRA
I am a biologist and aquatic ecologist. My research revolves around aquatic ecology and delving into the intricate interactions between humans and aquatic ecosystems. My expertise spans community ecology, as well as molecular ecology. At present, my Ph.D. project focuses on investigating the repercussions of human-induced stress on fish populations across various European catchments. I am examining their responses at both the population and molecular levels to gain a comprehensive understanding of the impacts.

SVENJA M. GILLMANN
I am a freshwater ecologist who studies the communities of small animals that live at the bottom of streams, called benthic invertebrates (e.g., freshwater shrimp, insect larvae). My Ph.D. project focuses on how these communities recover after the conditions in the stream have been improved due to restoration measures. Therefore, I collect benthic invertebrates from streams and identify them in the lab. I want to understand how their ability to tolerate various environmental conditions, to interact with other species, and to move around helps them find a place in a community.

SHAISTA KHALIQ
I am an analytical chemist. I dive into the science of small stuff, using high-tech tools to uncover what animals eat. Imagine atoms as puzzle pieces—some, called isotopes, are heavier. Think of me as a puzzle solver, figuring out an animal's diet by looking at these isotopes in amino acids, the building blocks of life. For instance, I can tell if a bear had a sushi feast or a berry blast! My Ph.D. project focuses on these techniques to understand how creatures adapt and interact in their environments, like detectives in the food web.

ANNABEL KUPPELS
I am an ecologist working with mathematical food web models. My research focuses on the mechanisms that lead to changes within food webs and communities that are affected by stressors such as temperature changes or salt stress. With the help of computer programs, I simulate stressor scenarios and study the changes in population dynamics to find possible solutions for repairing the food web. Through the simulations, I can also determine whether reintroductions after the loss of a species can be used to repair the food web.

GRACIELA M. MADARIAGA
I am a marine biologist working with species distribution models (SDMs). In a nutshell, I create maps to know where an animal, plant, or other organism can be found, or where they would not survive. A SDM uses information about the conditions in the environment such as temperature, rain, and whether an area is high (mountains) or low (valleys), to predict whether an organism can be located there, based on what the creature likes. In my Ph.D. research, I study how stressors (warmer temperatures, more salt in rivers) can affect the places where species can survive. This information can help us protect nature in the future.

KRISTIN PETERS

I am a hydrologist working with computer simulations that show me how rain is distributed in the landscape and how it forms rivers. It can also calculate other environmental variables, such as water temperature. In my Ph.D. research, I study the physical processes that affect water temperature. For example, if a river flows through a forest, the river water will not get as hot as it would if it flows through a field without trees. Correctly predicting water temperature can therefore help to estimate the response of species to temperature changes.

ALEXANDRA SCHLENKER

I am a freshwater ecologist working on river food webs and interested in what animals eat. Food webs not only tell us which species are present in our environment but also where they get their energy from and how they interact with each other (e.g., predator-prey relationships and competition). In my Ph.D., I am analyzing how stressors and stress recovery affect food webs. I do field samplings of river insects, fish, and potential food sources (e.g., algae, leaves, and plants). I analyze the animals' stomach contents and their chemical composition (stable isotope analysis) to identify their food sources.

DANIEL HERING

I am interested in rivers and other aquatic ecosystems and in the organisms that live there. I investigate how these organisms are adapted to environmental stress and how ecosystems respond to restoration. Besides experiments and field studies, I am also involved in practical restoration projects and investigate the effects of the measures implemented.

MATTHIJS VOS

I am an ecologist. In my group we aim to explain how biodiversity can be maintained and restored. We are especially interested in how this can be achieved in ecosystems increasingly challenged by climate change. For that purpose, we use laboratory experiments, field work, and ecological computer modeling. This helps us to study diverse networks of interacting animals and plants, both on land and in water.