PERSPECTIVES

ECOLOGY

How to survive in a human-dominated world

Mating between species can yield adaptive genes that facilitate species survival

By **Karin S. Pfennig**

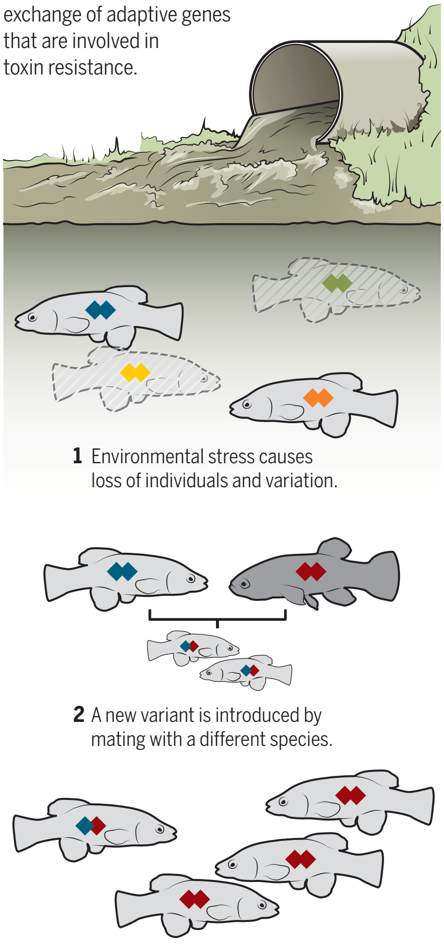
Humans are altering Earth's systems to such an extent that the geological period in which we are living has been dubbed the Anthropocene (*1*). Climate change, human land use, and the chemicals used in everyday living challenge biological species by creating new environments to which they must rapidly adapt or go extinct (*1*, *2*). Can species evolve fast enough to survive? On page 455 of this issue, Oziolor *et al.* (*3*) show that the answer can be yes. The authors report that a fish species rapidly adapted to toxins in a highly polluted region of the Gulf of Mexico. They identify gene exchange between species by hybridization (introgression) as the mechanism enabling rapid adaptation and rescue of populations that might have otherwise gone extinct.

Traditionally, scientists have considered adaptive evolution to be a slow process. Yet, an increasing number of studies have shown that species can adapt rapidly to environmental challenges (*2*). Such rapid adaptation provides hope that species can adapt to the profound changes occurring in our human-dominated world. Failure to adapt means that species go locally, and possibly globally, extinct. The challenge for biologists is to explain why some species rapidly adapt when others fail. The stakes for solving this challenge are high: Humans are inducing one of Earth's mass extinction events (*4*), and a better understanding of when and how species adapt to environmental stressors can provide critical information for conservation efforts.

A key determinant of adaptive potential is how much genetic variation a population harbors. When such variation is present, populations confronted with environmental change can potentially respond through rapid evolutionary change. Without genetic variation, a population cannot evolve. The problem is that, when populations experience environmental challenges, population size declines because individuals die or fail to reproduce. And when populations lose individuals, they lose variation too. The result is a negative feedback loop. The more individuals die or fail to reproduce, the less likely it becomes that a population can adapt; the less adapted a population, the more individuals die or don't reproduce. Breaking out of this feedback loop requires an influx of new genetic variation. Populations typically acquire this new variation through mutation or gene flow from other populations. Yet, adaptive mutations might not arise quickly enough to rescue declining populations before they go extinct, and gene flow from other populations often brings in variation that is only adaptive in the population's old environment, not the new one (*4*).

Adapting to pollution

Oziolor *et al*. show that Gulf killifish rapidly adapted to toxins in a polluted region of the Gulf of Mexico after mating with a related fish species, Atlantic killifish. This hybridization resulted in the exchange of adaptive genes that are involved in toxin resistance.



1 Environmental stress causes loss of individuals and variation.

2 A new variant is introduced by mating with a different species.

3 The new variant enables adaptation, and the population recovers.

GRAPHIC: V. ALTOUNIAN/*SCIENCE*

Hybridization between species is a crucial source of genetic variation that can fuel adaptation to new environments (*5*–*7*). But hybridization can also be an evolutionary dead end and a threat to diversity; it can reduce population fitness and cause species to collapse. Given that new species are increasingly introduced into many habitats through trade and other human activities, hybridization's role as a creative force, as opposed to a destructive one, is a controversial issue of pressing importance (*8*, *9*).

Oziolor *et al.* address this problem by asking whether hybridization has rescued declining populations of Gulf killifish (*Fundulus grandis*) by facilitating rapid adaptation to a new human threat. Using population surveys and experimental measures of toxic resistance, they show that Gulf killifish from polluted areas in Galveston Bay, USA, are resistant to toxins that cause lethal heart deformities. Using genomic analyses, the authors further show that populations in the most polluted areas were less genetically diverse than those in the less polluted habitat, as is expected if Gulf killifish population declined because of pollution (see the figure).

Oziolor *et al.* also report evidence of natural selection on genomic regions that include genes involved in the observed toxic resistance. The source of the adaptive genetic variation at these loci is a different species: the Atlantic killifish (*Fundulus heteroclitus*). The Gulf killifish appear to have acquired these genetic variants by mating (hybridizing) with the Atlantic killifish.

It is unclear why Atlantic killifish harbor genetic variation that is adaptive in Gulf killifish experiencing pollution. This touches on a more general question regarding adaptive introgression: Is such variation favored by natural selection in the donor species? If so, hybridization might enable species to capture adaptive variants from other species that have already undergone the adap-

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tive process. Alternatively, genetic variation derived from the donor species might only be adaptive in the recipient species, depending on how that variation interacts with the rest of the recipient species' genome and environment. If this is so, it might be more difficult to predict under which conditions introgression will be adaptive.

Regardless of these considerations, Oziolor *et al.*'s results provide compelling evidence of evolutionary rescue of a declining population through hybridization. Ironically, humans might have provided the opportunity for such rescue. Whereas Gulf killifish are found in the Gulf of Mexico, Atlantic killifish are normally found along the Atlantic coast of North America, outside of the geographic region where the Gulf killifish occur. Oziolor *et al.* suggest that the Atlantic killifish might have been transported by humans into Galveston Bay through discharge of ship ballast water. Thus, introduction of this species into Gulf killifish habitat by humans might have enabled hybridization—and therefore evolutionary rescue—to occur.

> ***"The challenge for biologists is to explain why some species rapidly adapt when others fail."***

The process of adaptive introgression observed by Oziolor *et al.* is not specific to extreme situations of human-introduced species or human-impacted environments. Genomic studies have revealed that hybridization is more common than expected in many species and that it might have fueled bursts of adaptive diversification throughout Earth's evolutionary history (*6, 7, 10*). But despite its potential to contribute to diversity, hybridization carries risks and can even threaten species with extinction (*8, 9*). To guide conservation efforts, scientists need to clarify the conditions under which hybridization diminishes rather than enhances biodiversity in a rapidly changing world. ■

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PLANETARY SCIENCE

What makes a planet habitable?

Efforts to identify habitable planets must look beyond atmospheres to planetary interiors

By **Anat Shahar, Peter Driscoll, Alycia Weinberger, George Cody**

The Milky Way Galaxy teems with planetary systems, most of which are unlike our own (*1*). It is tempting to assume that life can only originate on a planet that is similar to Earth, but different kinds of planets may be able to sustain Earth-like features that could be important for habitability. To focus the search for extraterrestrial life, scientists must assess which features of Earth are essential to the development and sustenance of life for billions of years and whether the formation of such planets is common. External effects such as stellar variability and orbital stability can affect habitability, but internal planetary processes that sustain a clement surface are essential to life; these processes are, however, difficult to characterize remotely. A combination of observations, experiments, and modeling are needed to understand the role of planetary interiors on habitability and guide the search for extraterrestrial life.

As exoplanet detection techniques improve, Earth-sized planets are likely to be found in the radiative habitable zone, that is, at distances from their host stars where they could have temperate (about 0° to 100°C) surface temperatures (*2*). This is important because to be habitable, a planet must be able to buffer life from extreme (globally sterilizing) variations in temperature. Launched in 2018, NASA's Transiting Exoplanet Survey Satellite has the capability to find small planets in the habitable zone of nearby stars and measure their radii (*3*). Ground-based telescopes are providing masses for such planets. Their densities provide a first-order constraint on composition, although it is likely that several different possible compositions can be inferred from the same density (*4*). Planets with compositions that differ from those of planets in our Solar System have been largely ignored, even though a wide range of stellar compositions and planetary densities have been discovered. The discovery of life elsewhere in the Solar System, for example on an icy satellite, would also radically expand the types of planets that need to be considered. The James Webb Space Telescope, due to launch in 2021, will attempt to detect atmospheres of the most favorable planets for life, but detailed measurements of atmospheric composition will require future extremely large telescopes on the ground and in space.

ATMOSPHERIC SIGNATURES OF LIFE

Atmospheric composition will be the primary observable that could imply the presence of life (*5*). However, identifying a biological signature in a planet's atmosphere requires an understanding of the possible compositions of abiotic atmospheres. The presence of free oxygen or an atmosphere out of chemical equilibrium could be signatures of life processes, but neither is definitive because atmospheres change over time and are open systems that are subject to complex sources and sinks. Volcanic eruptions release gases from the planetary interior that are the product of melting and magma migration. Atmospheric weathering can draw down noncondensable species, like carbon dioxide from Earth's atmosphere, to the seafloor, where they can be recycled back into the interior at subduction zones. All these processes are linked to the bulk composition of the planet and will evolve over time.

It remains unclear, therefore, what inferences can be made about the planet's habitability from its atmosphere before understanding more about how the atmosphere is tied to the interior dynamics and evolution of the solid planet. To advance this understanding, exoplanet atmospheres, which give a valuable snapshot of the surface composition, should be combined with experimental and modeling constraints on the interactions between the atmosphere and interior over long time scales.

INTERIOR PROCESSES SUSTAINING LIFE

On Earth, the environment needed for life to exist and be sustained is rooted in the presence of a stable hydrosphere and atmo-

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