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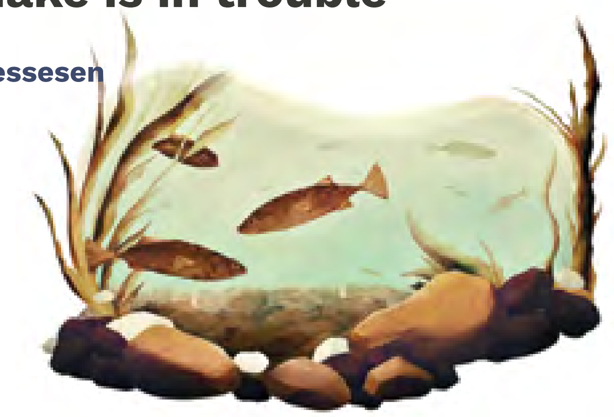

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editor's note

Cover art **Mohith O**

In this issue, we explore how human actions—intentional or not — have reshaped ecosystems globally. From the lasting environmental impacts of settler colonialism in Laikipia, Kenya, to the rich biodiversity of the Kutch district's desert landscape in India, these articles illuminate both the fragility and resilience of natural habitats.

We spotlight conservation challenges ranging from the invasive American bullfrog in wetland ecosystems to the reintroduction of three-spined stickleback to restored habitats for which they are no longer adapted. Both stories underscore the importance of holistic conservation efforts that consider ecosystem dynamics as well as contemporary evolutionary processes.

Our coverage extends beyond terrestrial realms, as we examine Costa Rica's unique tropical fjord and its endemic Yellow Sea Snake. And we also embark on a journey with monarch butterflies, exploring their incredible two-way migration and citizen science efforts that have helped answer critical questions about this unique phenomenon.

Rounding out this issue, we reflect on the ethical responsibility of researchers using cutting-edge imaging technologies to democratise science and improve the accessibility of this technology for conservation.

– Devathi Parashuram

Settler colonialism's prickly past

Author **Brock Bersaglio and Charis Enns** | *Illustrator* **Manvi Vakharia**

It is April 2023, and we are making our way across Laikipia in central Kenya. We travel down a public dirt road that cuts through a large, private wildlife conservancy. The road is lined by an electric fence on either side. Beyond the fence lies 58,000 acres of enclosed habitat for endangered and endemic species, including black rhinos, Grévy's zebra and wild dog. This conservancy also contains its own wildlife rescue centre, which offers sanctuary to some unexpected animals, including a pygmy hippo, a spotted owl and even a bear.

This part of Laikipia has been hit hard by successive years of drought. Although the rains have finally arrived elsewhere in the region, evidence of rain in these parts is scant. As we drive, large plumes of dust are propelled high into the sky. Behind the electric fences on either side of us, there are just a few tufts of grass and some common, hardy plants remaining, such as buffalo thorn (*Ziziphus mucronata)* and whistling thorn (V*achellia drepanolobium)*.

We are driving to Waso Centre in west Laikipia, passing through community-owned lands that make up the larger Naibunga Community Conservancy on the way. The fence of the private conservancy ends and a sudden and stark difference in ground cover makes the boundary between the private conservancy and the community-owned land clear. On the community side, the ground is almost entirely bare aside from cacti and succulents. As we drive on, more and more of the earth is covered by one distinct plant: *Opuntia* or prickly pear. The flat, oval stems of this cactus—loaded with long, needle-like spines—can be seen for miles, reaching up towards the sky out of the dusty soil.

Although impossible to know for certain, it is widely agreed that various species of *Opuntia* were imported to Kenya from South America by white settlers in the 1950s. Some say the plant was first brought to Kenya by a colonial homesteader in Dol Dol—just 12 kilometres from where we are driving to now. It was apparently kept as an ornamental potted plant that could survive in arid environments. Others report that colonial administrators used the cactus to construct living fences around their office buildings.

Some of the *Opuntia* species introduced to the region have since died off, but *Opuntia stricta* has thrived on community land. This species requires very little water to grow, which has allowed it to spread with relative ease. In 2018, the United States Forest Service was contracted to carry out a study on the spread of *Opuntia* in Naibunga Community Conservancy, which revealed that the species is present on 90 percent of the conservancy's landscape and completely dominates vegetation on 12 percent of the land.

As *Opuntia* spreads, it displaces and suppresses grasses vital for livestock and wildlife. In the absence of other options, animals graze on the prickly pears produced by the plants. The reddish-purple fruits pose grave injury to cattle, goats and sheep. The cactus spines lacerate the mouths of foraging livestock and can become lodged in their eyes, leading to blindness. Livestock also have trouble digesting the seeds of the fruit, which may clog the intestines of goats and sheep, leaving them unable to feed and ultimately causing their demise.

In places like Naibunga, where livestock keeping is people's main source of livelihood, this ecological legacy of colonisation has become a persistent thorn in the flesh of pastoralists and is of growing concern for some types of wildlife as the plant continues to reproduce and spread. Many across the conservancy are attempting to take action, removing the plant and replacing it with indigenous grasses and shrubs, but *Opuntia* is difficult to control. As we carry on towards Waso, we pass through areas where local residents and civil society organisations have been attempting to carry out this work. The plant has been dug up and left in large mounds on the side of the road. In some areas, potholes have been filled with the uprooted remains of the plants. In some ways, these extreme efforts are a symbolic testament to the durability of prickly pears as a species and the ecological legacy of colonisation.

Paradoxically, use of *Opuntia* as a pothole filler has contributed to the plant's spread. As vehicles pass over the flowers, fruits and stems, pieces of cactus penetrate tyres, hitching a ride across the landscape, propagating across the arid landscape and spreading further. Most scholarship on settler colonialism draws attention to how settler colonial power endures through political institutions, land use policies and legislation. These forces and processes are all undeniably essential to sustaining settler colonialism. Yet, settler colonialism is also memorialised and lives on through ecological relations. As the story of *Opuntia* so aptly illustrates, the ecological relations produced through settler colonialism can continue to violently suppress, remove and erase indigenous lives—including human, animal and plant lives—well after formal independence, just as other structural forces may.

All over the world, evidence of colonialism is detectable in the ecologies of post-colonies long after the official start of independence and end of empire. As Lenzner et al., 2022, write, "the persistent legacy of human activities on biological invasions over centuries [is] reflected in the compositional similarity and homogenisation of their floras". It was also intended that settler colonialism would impact on and endure through ecologies, including relationships between humans, animals and plants. The mid-20th Century writings of Elspeth Huxley, a white settler to Kenya, reflect the following sentiment:

"It is sometimes said that if Europeans were to withdraw from Africa today the continent and its people would revert to savagery and all traces of our civilisation would be expunged. This is not altogether true. Whatever the fate of our cultural influence, we should at least leave behind indelible traces of our cattle and sheep in the hereditary mechanism of animals which survived us. We should leave plants that have colonised the soil perhaps more permanently than men – wheat and barley, sisal and coffee, oats and tea, potatoes and peas, fruit and wattle trees. These at least would remain as a memorial to Europe's conquest of Africa." (Huxley, 1953)

Ecological imprinting is neither just an accident nor by product of settler colonialism, but has always been part of the mandate of colonisers. The 2020s have proven to be a crucial decade for biodiversity, following the IUCN World Conservation Congress in Marseille, France, and the adoption of the Kunming-Montreal Global Biodiversity Framework (GBF). A total of 188 governments signed onto the GBF, agreeing to coordinate and escalate efforts to halt and reverse the ongoing loss of marine and terrestrial biodiversity. With these commitments, massive amounts of funding are being made available to support the implementation of the GBF. The story of *Opuntia* in Laikipia, Kenya, is just one example of many that underscore the need to continue dismantling unjust ecological legacies of settler colonialism. Using GBF funding to directly support efforts to redress historical ecological injustices is therefore not only possible but essential for restoring and safeguarding healthier ecosystems for all people, animals and forms of life.

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Hidden Denizens of the Desert

Tracking carnivores in Kutch

Author & Photographer **Divyajyoti Ganguly**

Kutch's tropical thorn forest habitat is characterised by native *Acacia* trees on a lush grass bed post monsoon

The same habitat looks starkly different in the dry season

'Kutch'—what imagery comes to mind when you think of this place in the north-western frontier of Gujarat in India? Perhaps the White Rann—a salt desert, renowned for its immense size. I envisioned this as well. Hailing from eastern India, I could not fathom how the inhospitable desert with long spells of drought and scorching days with no shade to seek refuge under, could sustain any life at all. Kutch had always remained a distant mystery to me.

In 2019, an internship took me to the Banni grasslands towards the south of the White Rann. That was when I realised that the ecosystems here were not a monolith; they weren't cut from the same cloth. Travelling from north to south of the Kutch district, it is impossible to miss the stark shift from the desolate salt desert to the expansive grasslands, then onto wooded hills and ravines, and finally descending to meet the coastline.

Sighting of a jungle cat during 2022 fieldwork

The project that I was interning with focussed on meso-carnivores—the smaller yet more diverse and widely distributed relatives of large charismatic carnivores like tigers and lions. Kutch is known to be a haven for meso-carnivores such as jackals, foxes and small wild cats, among others. What adds to its intrigue is that it is also under substantial human use—by pastoral communities such as Maldharis and Rabaris, who have been following their traditional livelihood practices for hundreds of years, with their livestock (cows, buffaloes, sheep, goats and camel) and dogs. My work was largely restricted to a small part of the Banni and I was disheartened that I did not see a single meso-carnivore during my time there. Yet, I was also determined to return, to explore the wider landscape and search for these elusive animals.

Fast forward to 2022, I got the opportunity to return to Kutch. This time around, I was conducting my own research as part of my Master's dissertation fieldwork in the hills and ravines. My field timeline spanned the dry season—the harshest period in the desert ecosystem when animals must scramble for whatever limited resources are available. My previous experience in this landscape had offered a glimpse of how crucial the land was for humans beyond traditional pastoralism.

Sighting of an Indian fox during 2022 fieldwork

Agriculture was rapidly becoming a vital means of livelihood, infrastructure projects like mines and renewable energy farms (wind and solar) were on the upswing, and fresh roads were being carved out to facilitate these projects. Pursuing these ventures is relatively easy as much of this landscape retains the colonial tag of a 'wasteland' under land use policy. This means that while meso-carnivores may be protected species as per Indian law, their habitats are not. My goal was to understand how numerous species of meso-carnivores managed to share the depleting habitat resources in such an environment. But first, I had to find them.

I went fully equipped with a team of interns and field collaborators, armed with some knowledge of carnivore natural history, camera traps and scat sampling kits. After spending the first few weeks of January 2022 liaising with local villagers, pastoralist communities and the Forest Department, we set out on our search for the meso-carnivores. While I had to wait to go back to the lab in Banga-

Checking a camera trap for photos of meso-carnivores

lore to genetically ID the scats, the camera traps yielded instant results. In a matter of a few days, we already had multiple sightings and camera-captures of the commoners—golden jackal, jungle cat and Indian fox. We also started encountering smaller carnivores like mongooses and civets, and wild herbivores—chinkara and nilgai. And of course, lots of humans, livestock and domestic dogs. But the rarer species like desert cats and ratels (honey badgers) eluded us.

During one of our routine surveys the following month, we stumbled upon an intriguing find—a set of distinctly 'floral' pugmarks, a clear indication that a striped hyena had traversed the same path as ours. We strategically placed a camera trap along the trail, hopeful that the hyena might use the path again. Two days later when we returned to retrieve the camera, it was nowhere in sight. The rope securing it to the tree had been torn. Panic set in—had the camera been stolen? After a thorough search, we found the camera around 70 metres from the original spot. It was damaged and bore tooth

Photo of the striped hyaena before it noticed the camera trap

marks all over. We excitedly returned to the field station to identify the culprit. As a series of images were unravelled on the computer, it became evident that a striped hyena had indeed encountered the camera during its early morning stroll. Intrigued by the device, it had tried to investigate further, resulting in the camera being dismantled and chewed up. Eventually, it seemed to have lost interest, dropped the camera and moved on.

On another day, while climbing up and down in a dry ravine, we chanced upon a scat with an unusual appearance. Investigation of its contents revealed that it belonged to a carnivore that had had a porcupine meal—the scat was full of sharp quills! We were intrigued. What carnivore would risk the sharp quills of a porcupine? Once again, we deployed a camera trap and left it for a couple of days. The first several photos were of hares, porcupines and jackals. Then came the night-time footage of a short, stocky creature—black in colour, sporting a dorsal band of light grey hair. It was a ratel! And as the subsequent photos popped up on the screen, we saw that there was not just one, but two of them together.

As the days progressed, other rare meso-carnivores like the desert cat and rusty-spotted cat started showing up in our camera traps. But the rarest of them all was still missing. With February nearing its end, the pleasant days of desert spring transitioned into the scorching days of summer heat. The unbearable heat, coupled with the seemingly lower prospects of finding any newer species, was tiring us out faster than before. Giving up wasn't an option, and so, with a substantial part of the landscape yet to be surveyed, we soldiered on.

Camera trap photo of the elusive honey badger

It was now March and we were out checking our camera traps. It was two in the afternoon as we reached the last camera for the day. The sun was at its highest, the air was warm and we were sweating profusely. On reaching a camera, I would always check as many pictures as possible right away. On the small screen of the camera, I struggled to identify the animal in the very first picture. It did not look like anything that we had recorded before. And as my vision adjusted to the glare, I could not believe my eyes. The lean body on long limbs, large ears sporting prominent tufts of black hair—we had photo-captured the caracal, the rarest meso-carnivore of the Indian desert. My teammates and I were thrilled beyond words. The unexpected but fortuitous encounter rejuvenated us and the subsequent two months of intensive fieldwork flew by with a new sense of hope and enthusiasm.

Mining activities and wind farms are expanding in the landscape, stripping it bare of its natural cover of grasses and trees

During my last few days in the field, I could not help but re-think how wrong I was about deserts being 'inhospitable'. I had recorded a whopping 13 species of carnivores during my surveys. But how do these species adapt to the extreme climate? At the same time, how will the expanding agricultural farms, the roads, the mines, the solar and the wind farms impact this landscape and its carnivores? How can we protect this region and its wildlife without excluding its people? I left Kutch with these questions burning in my mind, hoping to return soon to tackle their answers.

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Stickleback (and forth):
Evolution and ecosystem restoration

Author **Bonnie May** | *Illustrator* **Pooja Sreenivasan**

Restoration is defined as the return of an ecosystem to its condition prior to disturbance or degradation. But is restoration ever truly possible? Environmental conditions are constantly changing. So what happens to established ecosystems when a species is suddenly reintroduced?

Watershed restoration projects often occur in waterways that have experienced physical, chemical, and morphological changes caused by human activity. Dams, water diversions, pollution, and run-off can significantly transform ecosystems by impacting the species that can survive and thrive in new and changing conditions.

Across southern California, restoration initiatives have targeted the reintroduction of top predators such as trout or salmon to restore ecosystems to their historic conditions. While transplanting fish increases biodiversity, it can cause detrimental effects on existing species that have adapted and evolved to a habitat free of predators. Conservation efforts must recognise current ecosystem dynamics to holistically address the biodiversity and evolutionary impacts of human interference.

Evolutionary background

Consider the three-spined stickleback fish. This small freshwater species is found in inland and coastal waterways across southern California and the rest of North America. About 20,000 years ago, ancestral sticklebacks migrated from oceanic to freshwater habitats, mostly occupying lakes, rivers, and streams. This massive environmental shift meant that different populations of sticklebacks now faced new and different predators. While some populations retained a large pelvic fin and protective armour, sticklebacks in freshwater environments with few predators evolved to lose their armour over the course of several generations.

Today, there are 16 recognised and distinct species of sticklebacks globally, two of which are distinct three-spined stickleback species. These species have demonstrated physical adaptations rapidly across evolutionary timescales. Due to environmental shifts, resource availability and the presence of predators, three-spined sticklebacks have repeatedly colonised freshwater and oceanic habitats throughout history. As a result, they have expressed evolutionary changes in as few as ten generations.

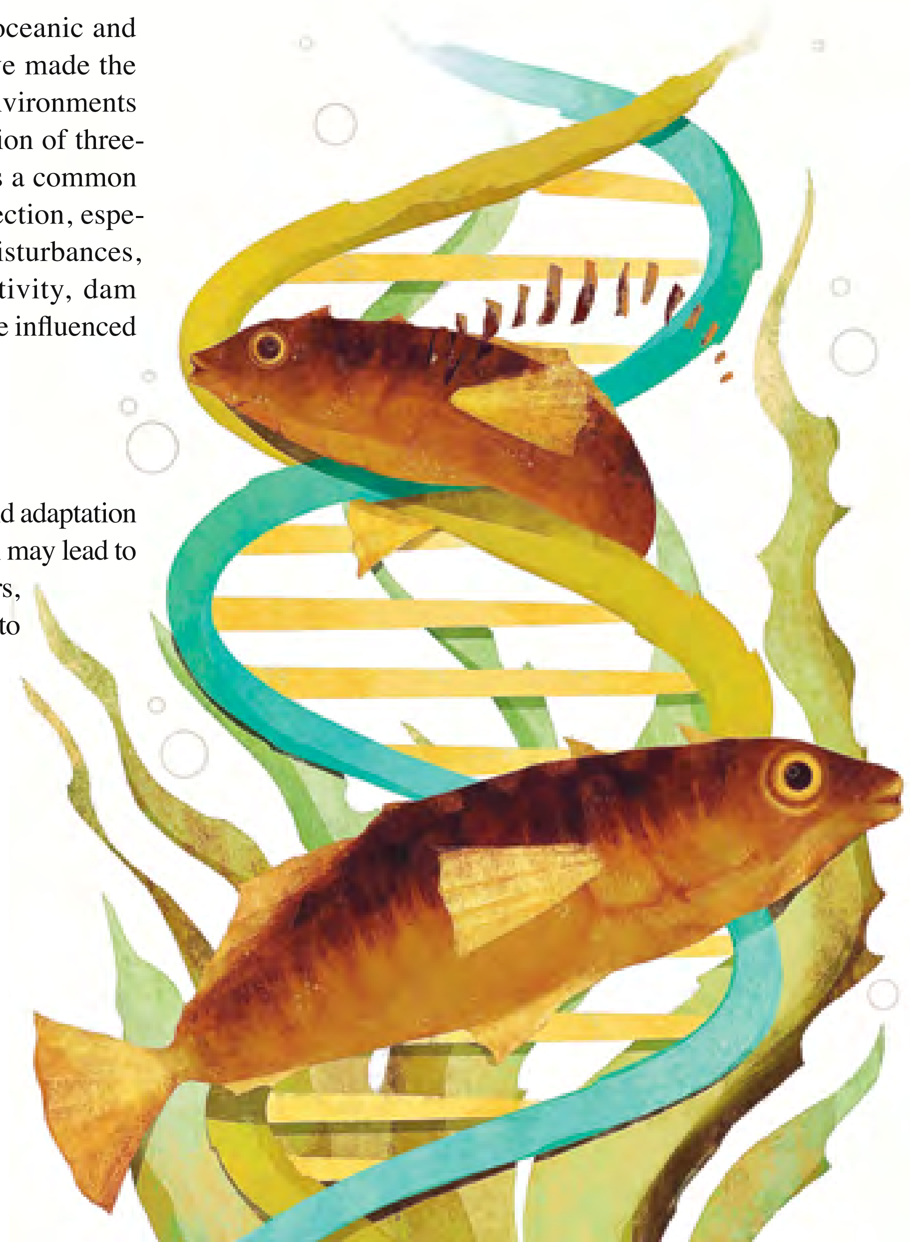
The movement of the species between oceanic and freshwater environments appears to have made the species uniquely resilient to changing environments and unforeseen threats. The rapid evolution of three-spined sticklebacks has made the species a common subject for studies related to natural selection, especially because modern human-caused disturbances, such as commercial and industrial activity, dam construction and watershed pollution, have influenced such evolutionary processes.

Modern pressures

Habitat alteration can influence evolution and adaptation through the separation of populations which may lead to different environmental conditions, predators, and other threats. Humans have contributed to the evolution of three-spined sticklebacks through the construction of dams and other forms of habitat degradation that separated the fish from their historic predators. Subsequently, many three-spined stickleback populations adapted to rivers without the necessity of anti-predator armour or behaviours.

Barriers such as dams reduce the connectivity of populations by restricting movement. This isolation inhibits breeding opportunities between populations and impacts the genetic diversity of a population. Genetic diversity is important for survival and reproduction, allowing species to adapt to potential environmental changes. Limited breeding opportunities can lead to inbreeding, which decreases population resilience against environmental threats.

In highly industrialised areas, human alterations to water quality can include increased salinity or temperature due to run-off or drainage. While these changes can be detrimental to marine species, some have evolved to accommodate such pressures. For example, juvenile three-spined sticklebacks have displayed tolerance to the introduction of warm and salty water to freshwater habitats, exhibiting faster



growth and lower parasite burdens than those in undisturbed freshwater habitats. The uninhibited growth of juveniles in altered environments illustrates the ways in which the evolutionary history of sticklebacks allows for movement between oceanic and freshwater environments with minimal detrimental effects.

Conservation implications

Rapid adaptation does not mean that three-spined sticklebacks are invulnerable to environmental changes. Although they have demonstrated the ability to adapt to a changing environment, populations may suffer in the long term if adaptive benefits are not uniform across all life stages. Threats or stressors may vary from one generation to the next. So, a beneficial adaptation can quickly become a hindrance in the event that environmental conditions change again. Three-spined stickleback populations seem incredibly resilient in the face of human pressures due to learned and evolved behaviours. However, a lasting ecological consequence of environmental disturbance is increased population vulnerability, particularly when restoration efforts occur without addressing recent environmental adaptations.

For example, if three-spined sticklebacks are reintroduced to a restored environment for which they are no longer adapted, or if non-native species are introduced into their range, stickleback populations may be negatively impacted. Populations may be vulnerable to new predators, environmental threats, lack of adequate habitats or nutrients, or newly introduced bacteria and diseases. The acknowledgment of the perceived resilience of the three-spined stickleback must be met with the understanding that the species is not immune to population decline. Three-spined stickleback fish have demonstrated the potential for rapid evolution throughout history. Nevertheless, the compounded effects of environmental destruction and disturbance pose a threat to the resilience of freshwater fish populations. It is also important to recognise that environmental changes caused by human activity occur much more quickly than natural species migrations or physical environmental shifts.

The migration of three-spined sticklebacks from oceanic to freshwater environments resulted in the loss of their protective armour, hind fins, and anti-predator behaviour because of reduced predation in lakes and streams, typically attributed to overfishing of predators or dam construction that separated species. However, predatory fish have been reintroduced to some freshwater environments to diversify riverine ecosystems.

The reintroduction of predators can lead to "reversed selection" in the three-spined stickleback, where the fish responds to changing environmental conditions with an increase or decrease in armoured plates within just a few decades. They have been observed to exhibit forms of more or less armour, some even resembling previous generations, in response to changes to their ecosystems and predators. Therefore, the reintroduction of predators into lakes and streams to increase biodiversity can have inadvertent evolutionary impacts on existing populations. In the same way that three-spined sticklebacks may experience adverse impacts due to the introduction of non-native species, the reintroduction of predators can present sudden and significant pressures on an ecosystem in which species have already adapted to the absence of predators.

Stocking predators in rivers full of unarmored sticklebacks can result in a 'genetic bottleneck'—an event that significantly reduces the population size of a species, resulting in limited genetic diversity. Human disturbances such as agricultural activity, run-off, oxygen consumption, or pollution can also cause genetic bottlenecks. Populations of three-spined sticklebacks in polluted freshwater environments have experienced bottlenecks, inbreeding, and reduced genetic diversity. A lack of interbreeding and genetic mixing creates the potential for isolation that reduces a population's resistance to certain pressures. Bottleneck events can be catastrophic for marine populations when low genetic diversity results in mass vulnerability to diseases.

Conservation in context: Case studies from California

In 2015, three-spined sticklebacks were reintroduced to Mountain Lake in Presidio, California, by transplanting the fish from a single nearby population. The three-spined stickleback is the only fish species native to Mountain Lake, but the introduction of predatory fish throughout the 20^{th} century led to dwindling populations and unprecedented habitat loss. This reintroduction effort was an element of a larger holistic strategy to restore and enhance fish populations in the lake, hinging on the role of the three-spined stickleback as a critical host species for California floater mussels.

However, in 2020, nearly all of the reintroduced population died due to exposure to disease. The deaths were associated with low genetic diversity caused by bottleneck due to translocation. In response to this die-off, a second reintroduction has been planned with the inclusion of sticklebacks from multiple nearby populations with the hopes that increased genetic diversity will improve the population's resistance to disease and other threats. Therefore, although genetic isolation and bottleneck events do not necessarily have a significant impact on reproduction, a lack of genetic diversity can leave populations vulnerable to calamitous circumstances.

Beyond genetic diversity considerations, hydrological conditions are a critical element of a comprehensive strategy in reintroduction efforts. In 2014, for example, several populations of three-spined sticklebacks were translocated within California from the Santa Clara River to the Santa Francisquito Creek due to extreme drought conditions that diminished available habitat. Translocation efforts identified sites in the creek with reliable water flows and compatible habitats, and fish were gradually acclimated to the new release waters prior to translocation. However, even after rescue efforts, prolonged extreme drought caused vast portions of the Santa Clara River to become uninhabitable for the three-spined stickleback. Monitoring efforts continued in the years following release, but drought, debris build-up in the creek and complex hydrological and morphological features have resulted in minimal observations of three-spined stickleback populations. In many cases, populations were unable to migrate or recover from unforgiving drought conditions.

In the context of reintroduction and restoration, the preservation of genetic diversity and healthy populations must be considered in relation to their evolutionary potential. Further, the physical conditions of the reintroduction site—including the presence of other species, hydrological conditions, and climatic hazards—greatly influence the health and mortality rates of the reintroduced species. Despite the astounding rapid changes that can occur among three-spined sticklebacks, predator introduction and species translocation present a sudden and considerable threat. Populations may be able to adapt over time, but they may not be able to recover.

Conservation considerations

How, then, can we restore ecosystems without causing catastrophic damage to existing populations? Conservation efforts and watershed management ought to consider the genetic diversity and evolutionary patterns of resident species, such as the three-spined stickleback, before causing physical alterations to a riverine habitat or reintroducing native predators to an environment. They must also consider how an environment has changed over time, how resident species have adapted to current conditions, whether current populations can handle sudden environmental shifts or an influx of predators, how human interference may support biodiversity, and the evolutionary implications of human interference.

Reintroduction is dependent on numerous variables within a particular environmental context. Differences in water quality and chemical composition, the presence of dams or non-native predator species, and the regional climatic conditions that present environmental hazards, for example, can dictate the health and productivity of reintroduced species. These variables may change depending on context—human-imposed habitat fragmentation via barriers often occurs along rivers, while the introduction of non-native species is commonplace in lakes. While the three-spined stickleback may be native to waters across the world, its ability to survive under particular conditions and stressors is dependent on a holistic approach to reintroduction that maintains a balanced ecosystem.

Connectivity is an increasingly prevalent topic in conservation, particularly in the context of urban rivers and streams where water pollution and habitat fragmentation lead to cascading impacts on watershed ecosystems. In the case of three-spined sticklebacks, changes in connectivity have led to rapid and measurable adaptations that can lead to population vulnerability. By incorporating predator-prey dynamics and long-term monitoring of ecosystem restoration planning efforts, conservation managers and practitioners can preserve biodiversity without causing cascading environmental impacts to populations and food webs that have adapted to a predator-free environment.

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Bullfrogs and native amphibians:

Four lessons about evolution

Author **Mariia Dvornikova** | *Illustrator* **Mohith O**

It is a quiet evening on Hazel Wolf Wetlands—a wildlife refuge located near Lake Sammamish, Washington. The sun is almost down. The light breeze from the wetland makes me feel chilly. I close my eyes and listen. *Conk-la-ree!* calls the red-winged blackbird from the bushes. *Wibit!Wibit!* responds frogs. The place is so calming. It takes me away from the hustle of the city and brings all my thoughts to this pond.

It feels like this pond, surrounded by a quickly and dramatically changing urban landscape, hasn't changed much in the past centuries. Yet I know this is a deceptive impression. If we only knew where and how to look, we would see the drama of species extinctions and introductions and the intricacies of species interactions unfolding here. We can witness a process that has been shaping life on Earth from the beginning of time.

Ongoing change

Many of us, including myself, used to think about evolution as a process that takes thousands of years. However, sometimes it can occur very quickly, within just a few generations. Scientists even have a special term for it—rapid evolution. As evolutionary biologist Theodosius Dobzhansky once said: “Nothing in biology makes sense except in the light of evolution.” Biodiversity conservation is no exception. If we want to save a species, we have to understand what evolutionary processes it undergoes. Otherwise, the conservation programmes might bring unexpected and undesirable results.

In wetlands such as Hazel Wolf, many native species of frogs and salamanders share their home with the invasive American bullfrog (*Lithobates catesbeianus*). It was brought to the Pacific Northwest a century ago and reared to consume frog legs. Husbandry farms in the region sunk into oblivion long ago. Bullfrogs have stayed, however. Establishment of exotic species in new habitats that have a negative impact on the ecosystem are called biological invasions. Worldwide, bio-invasions are one of the largest drivers of biodiversity loss. Bullfrogs impact native species of amphibians through predation, competition for food and novel diseases. At the same time, novel interactions between invaders and local ecosystems can give us valuable insights into the process of evolution. We could use these insights to inform more effective conservation efforts.

Let’s take a closer look at our wetlands. They can teach us valuable lessons about evolution and conservation!

Lesson one: It doesn’t take many, or What do the population of bullfrogs and the phoenix bird have in common?

Whether we want it or not, bio-invasions in a globalised world happen frequently. There is hardly any ecosystem that has not been impacted by invasive species. But how exactly do they happen? And how many individuals does it take to establish a new population? The answers vary greatly for different species.

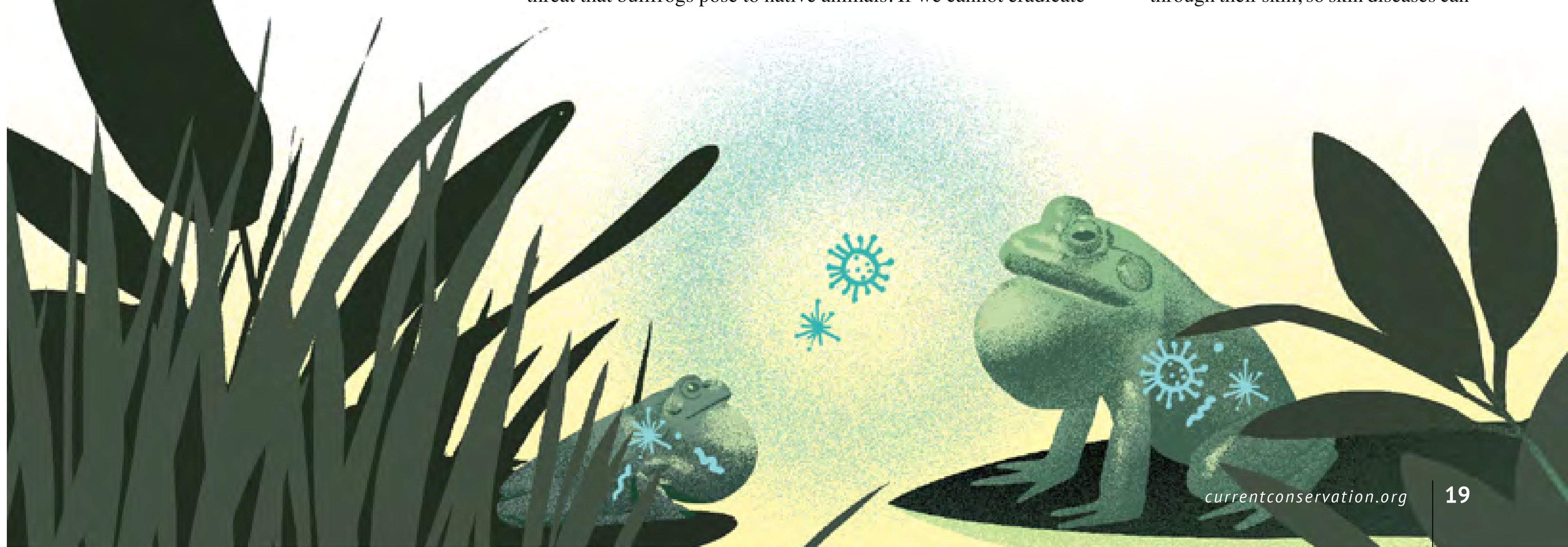
Imagining bullfrog invasions, I had always pictured hundreds of bullfrogs escaping a frog leg farm. I was mistaken! Astonishingly, as few as six female bullfrogs can start a new colony. Prolific bullfrogs can travel long distances to colonise new habitats, and females can lay as many as 20,000 eggs. All of these make eradicating an established bullfrog population a daunting task. Eradication efforts through trapping are labour intensive, expensive, and often fail—especially when undertaken alone. Take one, and two will come.

Do you remember the mythological phoenix bird—a symbol of immortality and resurrection? Similar to a phoenix rising from ashes, a bullfrog population, once established, resurges again and again. However, it does not mean that nothing can be done to reduce the threat that bullfrogs pose to native animals. If we cannot eradicate them, we can still control their population. Trapping, combined with pond draining or collection of egg clutches can be used to keep bullfrog populations at bay. Prevention, though, is the most effective conservation measure. Knowing that just a few individuals can start a new colony is a good reason not to release pets into a wild pond.

Lesson two: Genetic adaptations to new diseases are key to survival

When bullfrogs establish new colonies far away from their native range, they encounter new predators and diseases. Bullfrogs’ genes that code for immune response to pathogens can reshape quickly to better resist local pathogens, allowing their immune systems to adapt to the new environment. These changes in immune genes are heritable and are a great example of contemporary evolution. This makes bullfrogs successful invaders. Ironically, it also makes them a good vector for spreading diseases.

Contagious diseases are a global threat to amphibians. Amphibians breathe through their skin, so skin diseases can



be especially detrimental. Hence, all amphibians have skin secretions that protect them from pathogens. The antimicrobial properties of secretions differ greatly between species. They serve to best protect amphibians from pathogens they have evolved with, offering very little defence against new pathogens.

Chytridiomycosis is a skin disease in amphibians caused by a certain strain of a chytrid fungus. Bullfrogs likely carry the strain of the pathogen responsible for this disease in amphibians. Similar to travellers who might carry and unknowingly spread new variants of disease between countries and continents, invasive bullfrogs can carry and spread chytridiomycosis to previously uninfected ecosystems. Bullfrogs, meanwhile, co-evolved with this pathogen and are more tolerant to it than other amphibian species.

The ability of bullfrogs to spread chytridiomycosis explains why some communities of native amphibians experience more negative consequences than others amid bullfrog invasion. Communities of native amphibians with a different strain of chytrid fungus circulating usually have some level of immunity to chytridiomycosis and are less impacted. But communities that have had no exposure to chytrid fungus are more susceptible to severe declines and extinctions in the event of an outbreak.

For conservation managers, it adds a whole new level of complexity. With intensive efforts, an invasive bullfrog population can be controlled, minimising the impact of predation and competition on native species. But outbreaks of chytridiomycosis are hard to manage and have the potential to decimate entire populations of native amphibians.

Lesson three: It is not only bullfrogs who are adapting to the new environment. Native amphibians are adapting too!

Bullfrogs are voracious predators that will eat everything that will fit into their mouths. Unfortunately, most native amphibians fit the bill. If bullfrogs are present in the ecosystem, native amphibians have to find ways to avoid predation. Those amphibians who are more successful in avoiding predation and competition for food will have a better chance of reproducing.

Many species of frogs can 'scent' chemicals of predators they co-evolved with. However, if a predator is a new and unfamiliar species, it won't be recognised as a predator. For example, in ponds where a population of bullfrogs has been present for decades, tadpoles of California red-legged frogs *(Rana draytonii)* could detect their presence nearby and take shelter, but tadpoles from ponds free of bullfrogs did not exhibit the same behaviour. Interestingly, this behaviour is heritable.

This provides a glimmer of hope for the conservation of native amphibians, while also raising many questions that are yet to be answered. For example, can the population of native frogs be "taught" how to avoid bullfrogs? In theory, a relatively new conservation strategy called 'targeted gene flow', might benefit some species of native amphibians facing the bullfrog invasion. It involves the translocation of individuals with a favourable trait to populations that will benefit from this trait. The introduction of native amphibians who can already 'smell' bullfrogs and avoid them in a bullfrog-naive population can help the latter acquire this desired genetic adaptation.

Lesson four: Strong sexual preferences can lead to big troubles

Yes, you read it right. Males of red-legged frogs and Oregon spotted frogs (*Rana pretiosa*) prefer larger females for breeding. Who can blame them? In a harsh natural world, reproductive success is the main measure of success. Larger females mean more offspring. Mating with more fecund females has always been a beneficial strategy for males. At least, until bullfrogs arrived. Juvenile bullfrogs slightly resemble mature red-legged frog females, with one caveat—they are bigger. This makes them more attractive and almost irresistible to male red-legged frogs.

Not surprisingly, males are reluctant to mate with females of their own species. Instead, male red-legged frogs favour young bullfrog females. It is detrimental to reproductive success, as no offspring could be born from such courtship. It also puts males in great danger because mating with juvenile bullfrogs usually lasts longer—this might sound like a good thing in some circumstances, but not in a pond full of predators. Longer mating time increases the chance of males being eaten by adult bullfrogs or other predators. This behaviour poses a problem for conservation. With an increase in the number of bullfrogs in the habitat of Oregon spotted frogs or red-legged frogs, the higher the chances of males preferring to mate with juvenile bullfrogs, and sharper the population decline.

The sun sets in the Hazel Wolf Wetlands. As soft downs envelop the landscape, I reflect on how everything is interconnected, and how complex yet delicate the natural world is. I think about the ongoing changes in Hazel Wolf, how amazing bullfrogs are in their ability to adapt, and the whole new level of complexity that the evolutionary perspective brings to conservation.

It turns out that invasive bullfrogs impact native communities not only through predation and competition, but also by spreading new diseases and disrupting the reproductive process. We have to address these new threats to protect local ecosystems. If we fail to consider contemporary evolutionary processes in amphibian conservation programmes, the results of these programmes might be different from the expected outcomes.

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A THRILLING EVOLUTIONARY MURDER MYSTERY

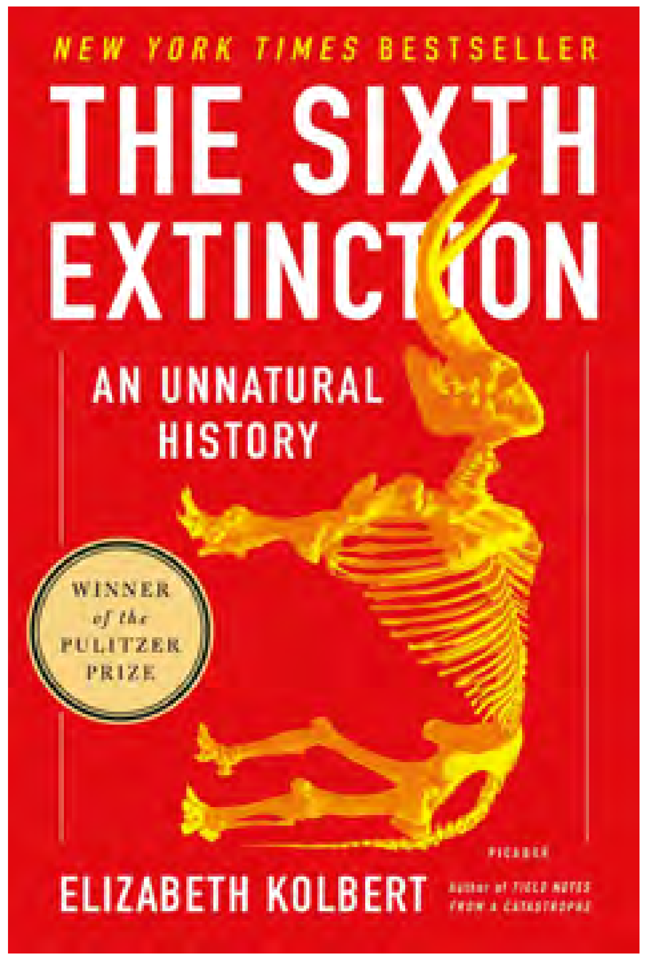
Author **Netra Kadambi**

It is the year 1830, and the scientific atmosphere in England is charged. Charles Lyell, a geologist whose work later influenced the young and impressionable Charles Darwin, is making waves in the scientific community. Lyell had just proposed a bold theory of species extinction via gradual changes in the landscape across millions of years. It defied the long-standing theory of extinction by sudden catastrophic events, as put forth by Georges Cuvier.

However, Lyell also mocked the idea of a fixed direction in the history of life, as propounded by Cuvier. He reckoned that the sequence of mammals arriving before reptiles and amphibians is not set in stone, contrary to what fossil records suggest. Extinct reptiles such as *Ichthyosaurus* can, under suitable conditions, reappear to reclaim the seas. In a hilarious rebuttal, Henry De La Beche, a fellow geologist, drew a comic titled "Awful Changes" starring a reappeared *Ichythyosaurus* donning a pair of spectacles and giving lessons to fellow Icthyosaurs on the extinct *Homo sapiens:*

> "You will at once perceive that the skull before us belonged to some of the lower order of animals; the teeth are very insignificant, the power of the jaws trifling, and altogether it seems wonderful how the creature could have procured food."

It is not just a dig at humans or the concept of resurrecting species but also at Charles Lyell and his nearsightedness. Such tussles in the scientific world serve as occasional subplots in *The Sixth Extinction* written by Elizabeth Kolbert and published by Henry Holt and Company in 2014. Kolbert uses these tidbits of history as a springboard to the main plot of the book, which concerns contemporary human-driven extinctions due to global warming, ocean acidification, habitat fragmentation and invasive species.



Kolbert begins each chapter by transporting us to a place and a time, be it on top of a ridge in the present-day Peruvian Andes or off the coast of Iceland in the 1800s. She describes the tell-tale signs of our influence on the landscape and its biodiversity through her own observations and conversations with scientists. Every chapter also features a species on the brink of extinction or already lost from our world.

Ichthyosaurs attending a lecture on fossilised human remains. Lithograph by Sir Henry de la Bèche, 1830, after his drawing. Image credit: Wellcome Images, a website operated by Wellcome Trust, a global charitable foundation based in the United Kingdom

Starting with scores of frogs mysteriously dropping dead across the Americas and Australasia, Kolbert traces their downfall and that of other species to a few culprits across 12 of the book's 13 chapters. She scrutinises each culprit's fingerprint in the present and past eras. During one of her many explorations, we learn that the oceans we are swimming in today are nearly 30 percent more acidic than they were during pre-industrial times. Global temperatures are around two degrees higher than they were two centuries ago. However, the clincher is that these levels are no strangers to our planet.

Many pages of life on Earth are filled with gorier periods of global warming, ocean acidification and ecosystem collapses. So, what is the difference between the past and the current extinctions? Does it matter if humans or a giant asteroid are to blame? Don't the consequences remain the same?

This book provides some clarity to these questions. Kolbert masterfully draws parallels between the extinctions of the past and what we are witnessing today. She eases even the most novice of her readers to complicated subjects by starting with something familiar and slowly building her way to the unfamiliar. Her liberal use of analogies allows us to navigate through complex concepts seamlessly. In one such instance, she uses a construction analogy to describe how carbonate ions needed to build coral reefs—in the form of calcium carbonate—are increasingly sequestered as carbonic acid in our relatively acidic oceans: "Imagine trying to build a house while someone keeps stealing your bricks." Such analogies make for a light read, even for people who find science daunting.

Aside from the writing style, the content itself is diverse and global. However, as a South Asian, I would have liked to see reportage from the Indian subcontinent. Its absence reflects the dearth of datasets and field studies in the region despite having some of the world's richest assemblage of flora and fauna. Nonetheless, Kolbert manages to underscore the global scale of the issues without mentioning South Asia. Further on, while discussing the extinction of large mammals such as mammoths, she describes how these extinctions coincided with the transcontinental spread of our species. She cursorily mentions an alternative theory of fluctuating climate without delving into the supporting evidence for the same. However, we have proof of recent ice ages restricting the ranges of these large mammals, with humans administering the final blow.

Despite a few shortcomings, Kolbert keeps her readers hooked throughout the book as if she is writing a thrilling murder mystery. However, unlike the macabre atmosphere of such novels, she adopts a matter-of-fact tone with some glints of drama and, surprisingly, humour for a rather grim subject. Her conversations with scientists are the only time we sense a tone switch. She alludes to the emotional turmoil researchers often experience when witnessing the large-scale demise of their beloved group of species. On the approaching extinction of coral reefs, she quotes J. E. N. Veron, a former scientist at the Australian Institute of Marine Science:

> "A few decades ago, I, myself, would have thought it ridiculous to imagine that reefs might have a limited lifespan. Yet here I am today, humbled to have spent the most productive scientific years of my life around the rich wonders of the underwater world, and utterly convinced that they will not be there for our children's children to enjoy."

You will appreciate Veron's sentiments better after reading Kolbert's beautiful take on coral reefs. Her comparison of coral reef ecosystems to "underwater rainforests" in the middle of a "marine Sahara"—followed by her justification for this imagery—evokes a sense of sadness at the thought that these ecosystems may not be around for long.

What stood out for me are a few occasions where Kolbert contemplates her place in the larger scheme of life. One such golden nugget is while she is collecting water samples at night in the Great Barrier Reef. All around her is darkness stretching from horizon to horizon; all she can see are the mighty stars above her. "The reason I'd come to the Great Barrier Reef was to write about the scale of human influence. And yet Schneider and I seemed very, very small in the unbroken dark."

Another moment is amongst army ants in the Amazon. She felt one needed to "paint oneself into a corner" to witness army ants in their millions, marching through the forest floor and ravaging anything along the way—including you if you panicked! Her description of our current era, reduced to a sediment layer no thicker than a "cigarette paper" in an unimaginably distant future, knocks out any lingering egocentric tendencies of a haughty reader.

You will soon realise that this book is not just about mighty army ants, dying frogs or breathtaking coral reefs. It is about all the rabbit holes of patterns that lost species of the past, present and future have fallen into, leading to their inevitable demise. It is about how extinction is a normal, slow-paced process, but also how the rates on a few rare occasions have shot sky high and brought life on Earth down to its knees. It is about the story of generations of scientists before us and their struggle to accept the concept of extinction, something Kolbert notes that even three-year-olds take for granted today as they play with their dinosaur figures. It is also about the extraordinary effort mankind has embarked on to save what is left, the tremendous irony of which you will appreciate after reading this book.

While we are almost sure that the extinct *Ichthyosaurus* will not reappear, Jan Zalasiewicz, an expert on extinct graptolites, predicts that giant rats will take over the world when the dust settles and the sixth extinction runs its course. He reckons a species or two may start "living in caves" and "wearing skins of other mammals" they kill to cover their nakedness. Henry De La Beche might have been more accurate if he had sketched Prof. *Rattus magnum* instead of Prof. *Ichthyosaurus*.

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Sitting on the wings of a butterfly

Author **Deborah Dutta**
Illustrator **Leeza John**

The first time I heard the term butterfly tagging, I was intrigued. I had heard of mammals and reptiles being tagged to help biologists understand their movements and behaviour, but what could one possibly attach to a butterfly? My mind conjured up strange images of butterflies sporting miniature collars on their abdomen, or some gizmo hoops on their wings. Thankfully, my wildly misplaced notions were soon going to be dispelled; I was attending a workshop on tagging monarch butterflies (*Danaus plexippus*).

It would be difficult to find a person who isn't enamoured, at least for a moment, by seemingly weightless wings glittering in the sunlight. Butterflies have been a motif and symbol in various cultures dating back to more than 3000 years. The ancient Greek word for "butterfly" is ψυχή (psȳchē), which translates to "soul" or "mind". Many Meso-American and Southeast Asian cultures believe butterflies to be reincarnations of the deceased, epitomising metamorphosis through its transition from a caterpillar to a winged creature.

Yet, despite their widespread popularity, butterflies are not as eternal as we would like them to be. In fact, they are dying in apocalyptic numbers along with other insects. A 2019 report in *Biological Conservation* mentions that 40 percent of all insect species are declining globally and one-third are critically endangered. Insects pollinate more than 80 percent of terrestrial plants and directly contribute to crop yields. Reducing the significance of an entire class of animals to their role in supporting human well-being is hardly justified, but even by these narrow parameters, the decline in insect populations should be of significant concern to us. It wouldn't be a stretch to claim that entire food webs and ecosystems could collapse if the trends continue. The tragedy of losing creatures that have survived and evolved for millions of years is hard to imagine.

These heavy thoughts were momentarily brushed aside by the graceful glide of a monarch butterfly, surfing the cool winds by the seaside where we had gathered to learn more about them. We were a motley group of nature enthusiasts and educators, united in our curiosity and fascination to better understand these enigmatic creatures. One of the most iconic pollinators among the North American butterflies, monarchs migrate annually across North and South America, making them the only known butterflies to embark on a two-way migration similar to birds. They are thought to have been given the name "monarch" in honour of King William III of England, as the butterfly's predominant rusty-orange colour matches the king's secondary title, 'Prince of Orange'. "Can you believe that we'll be seeing the great-grandchildren of these butterflies up north next year!" exclaimed our workshop host and naturalist, Kathy (name changed).

Unlike other butterflies that can withstand the winter as larvae, pupae, or even as adults in some species, monarchs cannot survive the cold winters of northern regions. Instead, every autumn, millions of monarch butterflies leave their summer breeding grounds in northeastern USA and Canada and travel more than 3,000 miles to reach overwintering grounds in southwestern Mexico. These 'super generations' of migrating monarchs are unique because though they are the same species, for reasons still unclear, they can survive for up to eight months, as compared to the much shorter lifespan of other monarch generations that do not migrate. Using air currents, they travel all the way back to Mexico—a feat as remarkable as it sounds. Some overwinter in southeastern and western parts of North America as well.

Known as Mariposa Monarca in Mexico, the monarchs huddle together by the millions on the branches of oyamel fir trees found in the mountains of Central Mexico. The humid microclimate and densely packed arrangement ensure that the butterflies survive the cold. After waiting out the winter, they head part of the way back north to warmer climates such as Texas, where they mate and lay eggs on milkweed plants. The larvae subsist exclusively on milkweed plants, which contain toxins in the sap. The caterpillars are able to store the toxins, known as cardiac glycosides, in even higher concentrations than what is found in the plant, and carry them in adult form too. As a result, most birds attempting to make a meal of the monarch find them unpalatable or are forced to vomit soon after consumption. The bright orange stands for 'Danger!' it seems.

"Their evolutionary defence has now become their weakest link though," explains Kathy holding a milkweed cutting that had two caterpillars munching on its leaves hungrily. Increased use of herbicides and shrinking habitats have led to the milkweed plant population declining by 21 percent between 1995 and 2013.

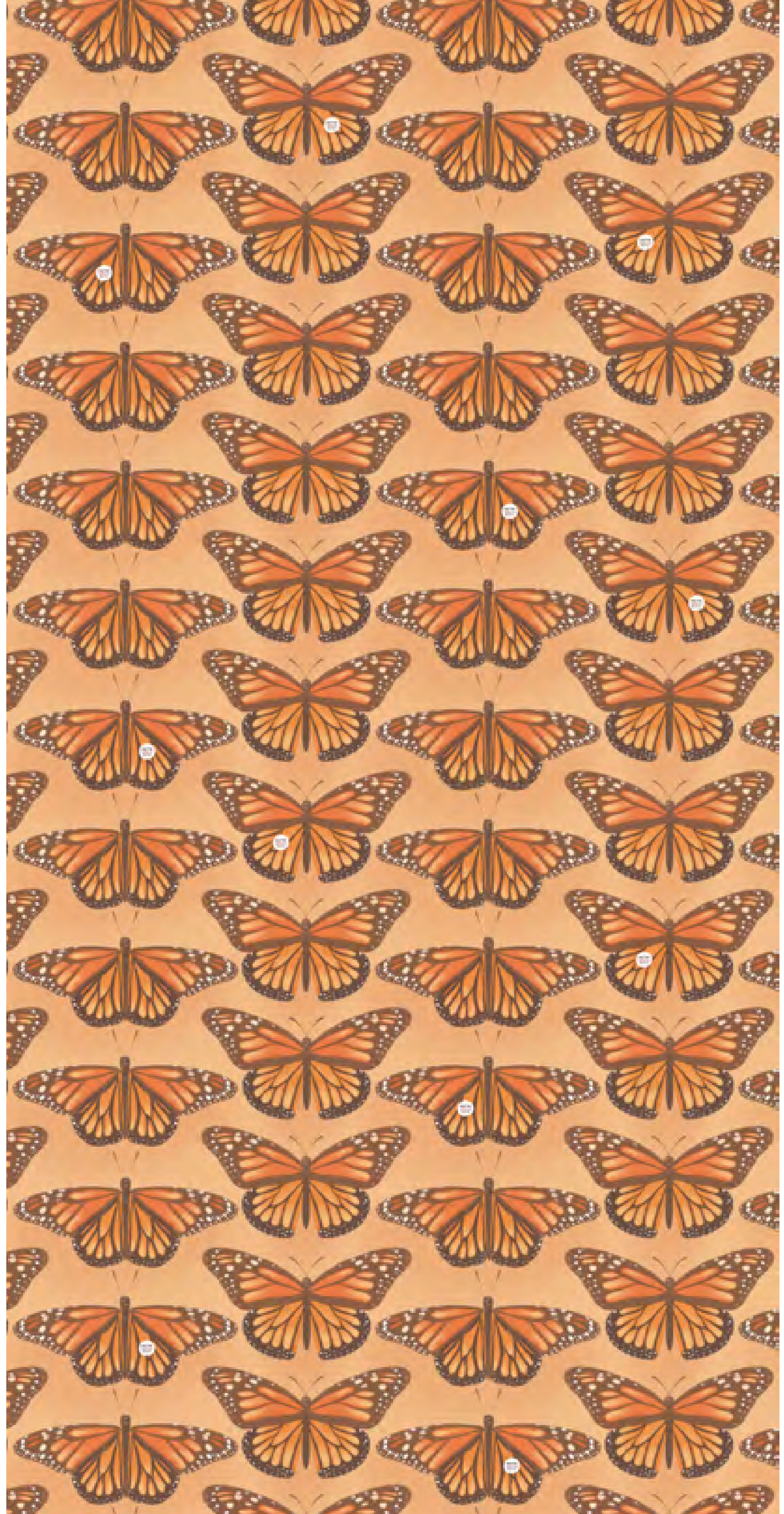
Almost mirroring the decline, the monarch population completing the winter migration dropped from 550 million in 2004 to a mere 33 million in 2013.

Apart from the generation that makes the long haul and overwinters in Mexico, each generation lives for two to four weeks, mating, laying eggs, and dying, and the next generation continues the journey upwards. "When you look at this butterfly, you are witnessing a multi-generational saga that has been going on for millions of years. But, in just a few decades, rampant loss of habitat and host plant has put them in peril. So, with the help of organisations like Monarch Watch, we do what we can. Plant, hope and tag," adds Kathy.

Founded in 1992, Monarch Watch is an outreach program focused on education, research and conservation related to monarch butterflies. Through citizen science efforts, the organisation has encouraged the revival of native milkweed species and habitat restoration within backyards, schools and parks. They also started the volunteer-driven tagging program by designing lightweight, circular tags with unique codes that can be attached to the butterflies in a specific manner such that the tags don't interfere with their flight or harm them in any way. With over a quarter of a million tags distributed each year, meticulous data are received from volunteers who tag and release the butterflies after recording the tag code, tag date, gender of the butterfly and geographic location. The efforts have helped answer critical questions about the pace and nature of the migration.

As much fun as butterfly tagging might sound, carefully capturing the butterflies is an exercise in patience and perseverance. We also had to be careful to catch the right ones! In a classic case of animal mimicry, butterflies such as viceroy and Gulf fritillary share similar patterns and shades as the monarch. After nearly an hour of hunching, running, crouching and jumping, we managed to capture only two with catching nets. Kathy explained how to hold the butterflies to ensure they are not hurt and slip them into a wax paper envelope so that all butterflies could be tagged in one session.

While holding one, I was surprised to feel the strong, almost claw-like grip of its hind legs, which Kathy explained helps them cling on to the edges of flowers



and plants. Kathy gently and expertly stuck a tag to the forewing and pointed to a black spot on a vein on each hindwing. "A male," she said. The spots contain scales that produce volatile chemicals called pheromones used during courtship. Kathy spoke of volunteers who have been tagging the monarchs for over two decades, awaiting their annual presence with hope and concern. The long-term data have been especially useful to understand trends and even locate other overwintering habitats that were not known earlier.

In India, similar citizen science projects have helped collect significant data about trees, birds, and plants. Consistent observation has often been the first step towards critical findings. For example, species of milkweed butterflies have been found to migrate between the Eastern and Western Ghats in southern India to escape the harsh summers.

After tagging the butterflies, we set them free, and they immediately took to the skies. Like winged messengers to a perilous and uncertain future, the monarchs seem to symbolise tenacity and resilience through their long journeys. In ensuring the continuity of their path and lifecycles, we can partake in some small measure, the wonder, beauty and danger that the world continues to churn.

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Leeza John ***is an illustrator who loves textures and patterns. She often leaves her digital tools to create art with everyday objects, hence her work is varied and constantly evolving.***

How can we make new conservation technology more accessible?

Author and Photographer **Orion McCarthy**

Technology often makes it feel like we are living in the future. For example, the last time I visited the dentist, the hygienist stuck a camera in my mouth, snapped hundreds of pictures in a matter of seconds, and then showed me a photo-realistic 3D model of my teeth (clearly identifying spots where I need to floss more). When I left the clinic, I opened Google Maps to get directions and was able to visualise a 3D reconstruction of the city block I was standing on. As I walked to my destination, I read a news article on my phone about an archaeological site halfway across the world, and was able to virtually tour a 3D reconstruction of the site generated from overlapping pictures.

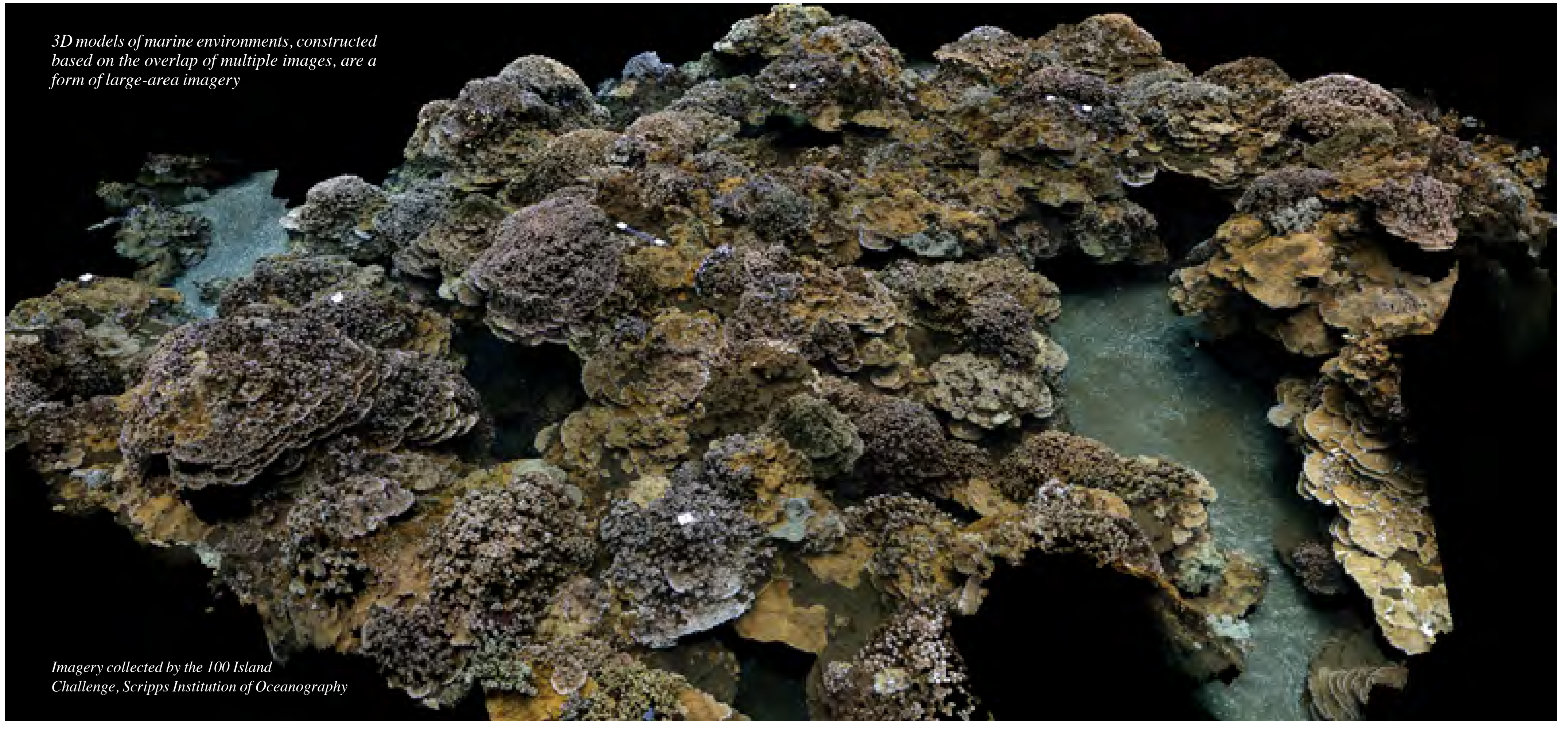
These innovations are all examples of a technology called large-area imaging, a type of photogrammetry that uses multiple overlapping images to reconstruct a high-resolution 3D model of a stationary object or environment, from the inside of my mouth to the Colosseum.

Beyond these everyday applications, large-area imaging also has immense potential as a conservation technology. Photo-realistic 3D models of ecosystems can provide a snapshot of environmental conditions and act as a visual record of change. Importantly, for places that are difficult to access—such as marine ecosystems—3D models can serve as a platform for researchers to conduct "virtual fieldwork" and for the general public to "visit" a remote place they would otherwise never get to see.

Large-area imaging has been used with increasing frequency in the marine sciences. In a recent study, led by Dr. Orion McCarthy from the Scripps Institution of Oceanography, we examine trends in the application of this emerging technology, focusing specifically on coral reefs. As part of our study, we also asked coral reef scientists and conservation practitioners how they would like to use large-area imaging, what obstacles they faced in trying to use large-area imaging and how those challenges could be overcome.

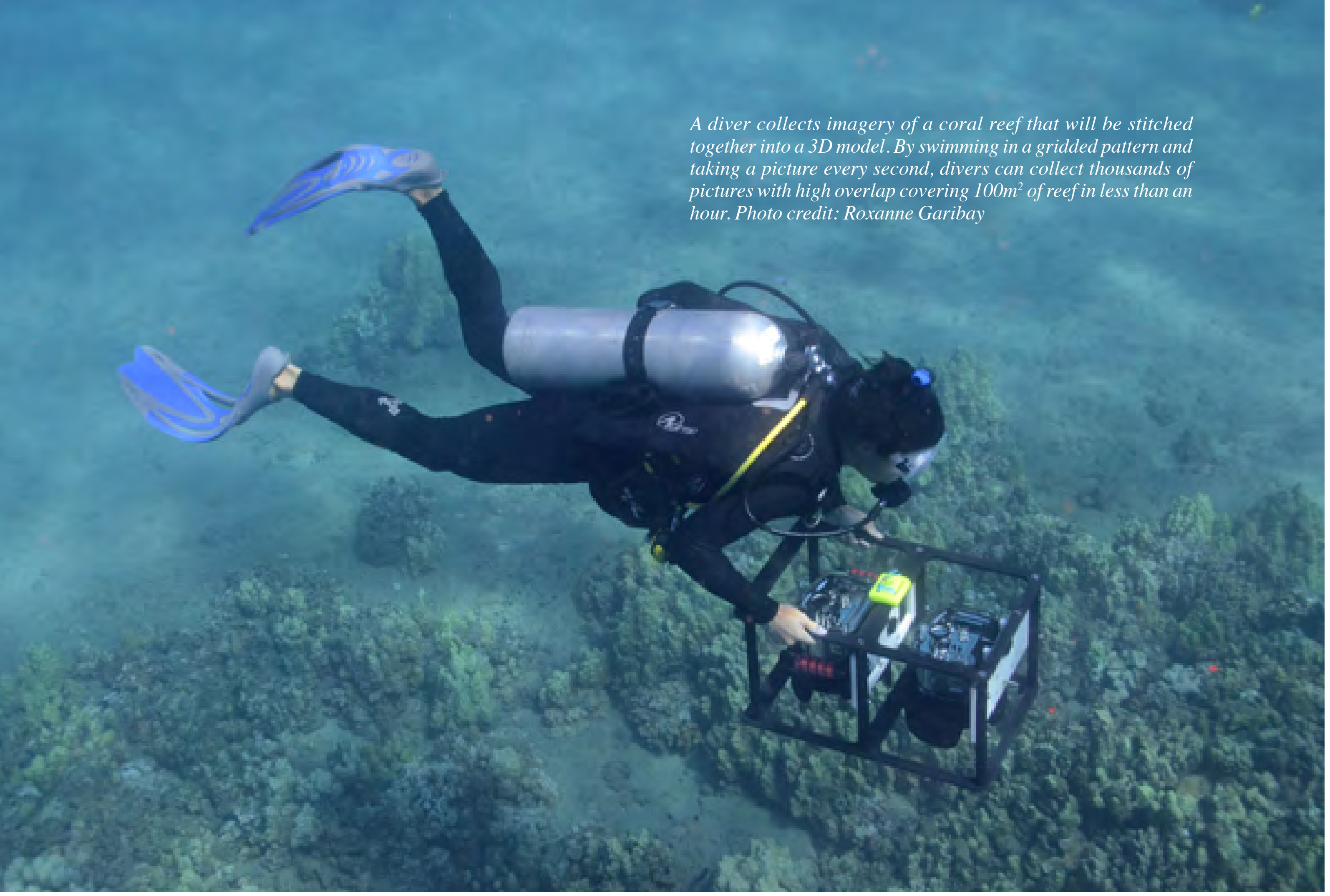
We found a mismatch between current research using large-area imaging and the research priorities identified by our survey participants. Despite the many potential applications of large-area imaging for conservation and the immense conservation needs of coral reefs, we found that few studies to date have utilised large-area imaging for applied conservation science, whether it is for tracking the fate of coral restoration projects or evaluating the effectiveness of marine protected areas. Instead, the bulk of research using this technology has focused on a narrow range of topics and has been conducted primarily by researchers based in wealthier countries. Furthermore, our survey participants identified many barriers to adopting large-area imagery, such as equipment cost, technical expertise and staff capacity.

Without taking concerted steps to make large-area imaging more accessible, we risk excluding researchers in less affluent countries, perpetuating parachute science and conducting research that is out of step with the needs of conservation practitioners. Scientists at well-resourced institutions that currently use large-area imaging have served as pioneers of this technology. These same researchers now have an ethical responsibility to make large-area imaging more accessible by facilitating the transfer of technology from the ivory tower to the hands of conservation practitioners.



3D models of marine environments, constructed based on the overlap of multiple images, are a form of large-area imagery

Imagery collected by the 100 Island Challenge, Scripps Institution of Oceanography



A diver collects imagery of a coral reef that will be stitched together into a 3D model. By swimming in a gridded pattern and taking a picture every second, divers can collect thousands of pictures with high overlap covering $100m^2$ of reef in less than an hour. Photo credit: Roxanne Garibay

Based on feedback from our survey participants, we provide a set of recommendations to improve the accessibility of this technology for marine conservation. This includes developing training materials, hosting workshops, fostering partnerships for data processing and analysis, establishing clear communications with partners, publishing clear pipelines and standardised methods, working with developers to improve the software and conducting conservation-relevant research using large-area imaging. These steps, among others, will help to maximise the positive impact of this emerging technology for conservation.

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Acknowledgements:

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Orion McCarthy ***is a marine biologist with expertise in coral reef ecology, conservation technology, and ecosystem restoration. He recently earned his doctorate from the Scripps Institution of Oceanography.***

Costa Rica's endemic sea snake is in trouble

Author **Brooke Bessesen**
Illustrator **P I Megha Vinod**

As we grapple with biodiversity loss around the globe, endemic populations that evolve in single locations likely disappear at faster rates. Their long-term survival depends on scientists securing data to understand potential threats and inform conservation policy. Unfortunately, even basic information such as an organism's habitat, its geographical range and factors that make its habitat suitable are often, and surprisingly, unknown—even for vulnerable taxa.

That was the case for the only sea snake endemic to the Americas. The bright yellow *Hydrophis platurus xanthos*, "Xanthos" for short, is found only in Golfo Dulce—a narrow tropical fjord in Costa Rica. The population of this curious sea snake is confined to a deep inner basin, isolated from the Pacific Ocean by a shallow outer basin. Based on our 2023 study of its range and habitat, Xanthos occupies just 260 square kilometres—an area small enough and threatened enough for this subspecies to be listed as Endangered on the International Union for Conservation of Nature (IUCN) Red List.

Using computer models to evaluate its environment, we found that Xanthos prefers deep waters. Indeed, the near-surface layers where it breathes, feeds and rests, are almost exclusively positioned over depths greater than 100 m (the maximum depth in Golfo Dulce is 215m). We also found that Xanthos favours slightly brackish waters with a salt concentration of about 3.1 percent, as opposed to the oceanic average of 3.5 percent. And it remains in areas with pH values closer to the historic oceanic level of 8.2 and higher levels of dissolved oxygen. These preferences indicate that climate change-driven ocean acidification and deoxygenation could threaten the population.

Climate change is leading to higher water temperatures which may bring other challenges too. Golfo Dulce is already relatively warm, with daytime temperatures greater than 32ºC, compared to an average of 28ºC in the open ocean. It is hypothesised that Xanthos has adapted to its warm habitat by evolving a lighter skin colour as well as a nocturnal activity cycle. Our research also shows that the snakes surface when top waters are cooler than average, perhaps to avoid excessive heat. If temperatures continue to rise, will Xanthos be able to adapt further?

Sadly, climate change is not the only threat to the population. While many still consider Golfo Dulce pristine, human impacts are rapidly increasing, including boat and ship traffic, as well as chemical runoff from marinas, communities and farms. Landlocked to the north and bound by shallows to the south, Xanthos cannot migrate elsewhere and so is left to face the dangers of propeller strikes and pollution. Protective action must be taken soon to safeguard this unique endemic subspecies.

It's worth noting that sea snakes can serve as bioindicators, forewarning of habitat decline. So, Xanthos could be a harbinger of change, the proverbial canary in Golfo Dulce. That means its' well-being is relevant to other species in Golfo Dulce. Endangered sea turtles, sharks and corals are all confronting the effects of seaside development and climate change, and their fates are interlinked. Thus, maintaining healthy habitat for these charismatic canary-coloured serpents will help ensure a vibrant future for all marine life in Costa Rica's unique tropical fjord.

Further Reading

Bessesen, B. L. B., C. Garrido-Cayul and M. González-Suárez. 2023. Habitat suitability and area of occupancy defined for rare New World sea snake. *Conservation Science and Practice* 5(1): e12865. doi.org/10.1111/csp2.12865.

Bessesen B, V. Udyawer, J. M. Crowe-Riddell, H. Lillywhite and K. Sanders. 2024. *Hydrophis platurus ssp. xanthos. The IUCN Red List of Threatened Species*. https://www.iucnredlist.org/species/239753560/239753681.

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