INSIGHTS

POLICY FORUM

Genomics-based detection of inbreeding among southern resident killer whales can help explain the population's lack of recovery.

50 YEARS OF THE ENDANGERED SPECIES ACT

A landmark environmental law looks ahead

In late December 1973, the United States enacted what some would come to call "the pitbull of environmental laws." In the 50 years since, the formidable regulatory teeth of the Endangered Species Act (ESA) have been credited with considerable successes, obliging agencies to draw upon the best available science to protect species and habitats. Yet human pressures continue to push the planet toward extinctions on a massive scale. With that prospect looming, and with scientific understanding ever changing, *Science* invited experts to discuss how the ESA has evolved and what its future might hold. **—Brad Wible**

Drawing from beyond the life sciences

By **Robert L. Fischman**[1] *and* **J. B. Ruhl**[2]

The ESA-implementing agencies, required by the ESA to follow the "best scientific and commercial data," enjoy respect for and build on long traditions of natural science expertise. Less often recognized is that many of the ESA's success stories drew mainly from the social sciences. These offer lessons for how to improve effectiveness of efforts under ESA.

Congress imposed prohibitions in the ESA that can create perverse incentives for landowners who face costs associated with the presence of protected species. For instance, because a certain minimum tree size is required for nesting by endangered red-cockaded woodpeckers, timberland owners were more likely to harvest trees before they reached that size and ESA protections were triggered (*1*). To reduce preemptive habitat suppression, in the 1990s the US Fish and Wildlife Service (USFWS) created a safe harbor program that encourages land managers to voluntarily provide habitat for species—even if temporary (e.g., trees big enough to host owl nests just until they grow to ideal harvest size)—in exchange for immunity from regulatory enforcement. This realigned incentives to generate greater conservation from private property (*2*).

Elinor Ostrom and others have documented the effectiveness of collaborative governance, typified by local, bottom-up, self-enforcing management approaches. The threat of ESA "harm" liability from incidentally injuring a protected animal can prompt large-scale multi-landowner projects that come closer in footprint to the range of a species than could any single property boundary. Rather than navigate ESA compliance property by property, landowners may devise a regional plan that will fulfill the statutory conservation man-

PHOTO: NOAA FISHERIES/VANCOUVER AQUARIUM VIA AP PHOTO date if they receive immunity for activities consistent with the plan. In this way ESA-implementing agencies created the conditions to spur collaborative conservation efforts pooling economic benefits by leveraging local knowledge, habitat ownership, and less burdensome compliance measures (*3*).

Some ESA agency rules incorporate public-private plans or best-management practices that transform the ESA's harm prohibition—focused on difficult-to-detect consequences such as injury—into programs promoting best practices adapted to particular circumstances in specific places (*4*). For instance, it would be impractical to detect harm from agricultural activities, such as plowing, to California's Mazama pocket gophers nestled in their burrows. But a tailored rule shields from liability any "accepted agricultural or horticultural (farming) practices" if soil disturbance does not penetrate deeper than a foot. That provides a clear standard for both farmers and regulators to track and allows agricultural activities to coexist with species recovery.

Conservation treatments in wildlife management commonly incorporate adaptive management to fine-tune (or abandon) plans to recover or sustain wildlife, iterating to reduce uncertainty through learning by doing (*5*). Yet adaptive management is hardly used to improve the programs and rules themselves that spur and govern adaptive conservation plans. That risks innovation drift if effectiveness is never precisely defined, measured, and used to trigger reevaluation. Agencies have adequately applied science to understand what makes innovations work and to fine-tune agency behaviors. Sometimes conservation science agencies need to turn their observational tools on themselves.

Going forward, an important research priority for the ESA is to understand better how to prompt human behavioral changes. Mere statutory prohibitions are not enough. The agencies should employ lessons from empirically tested models outside of conservation biology, genetics, and other life sciences. Like all environmental law, the ESA is—first and foremost—law governing humans, not the forces of nature.

Updating practices for the genomic era

By **Brenna R. Forester[3], Tanya M. Lama[4], Marty Kardos[5]**

Genetic data have been used for decades in ESA decision-making, most commonly for taxonomy and the delineation of subspecific units. Technological advances have made much larger genomic datasets available for at-risk species, improving the precision and resolution of metrics such as genetic diversity, while bringing previously inaccessible parameters like adaptive differentiation and individual inbreeding within reach. Although inferences from genomics can present challenges to established ESA practices, they also provide opportunities for innovation (*6*).

Genomic data advance ESA implementation in three areas: identification of listable units (i.e., species, subspecies, and distinct population segments), assessments of viability, and development of recovery strategies. Adaptive genomics, which improves our understanding of adaptive differentiation and evolutionary potential, is already being used to inform these three objectives (*7*). For example, these data can help describe "significance" in the designation of distinct population segments, by characterizing a species' adaptive diversity and evolutionary legacy. In a recent case, a small genomic region was found to be associated with the seasonal timing of spawning migration runs, an important life-history trait in Pacific salmon. This discovery challenged established approaches for defining significance in salmonid conservation units, suggesting the need for finer-scale delineations to conserve fish with the early-run life history. However, lack of reproductive isolation and genome-wide similarity among fish with different phenotypes resulted in a recommendation to retain existing larger-scale units. Additional research identifying the dominance patterns and evolutionary history of this genomic region underscored the importance of established guidelines to conserve phenotypic diversity within units, ensuring that recovery actions prioritize retention of early-run alleles to prevent irreversible loss of the phenotype (*8*).

Viability assessments and recovery efforts are also being improved by advances in the detection of inbreeding (mating between close relatives). Small, reproductively isolated populations are particularly susceptible to reduced fitness due to inbreeding (i.e., inbreeding depression). Runs of homozygosity (ROH), large continuously homozygous regions in the genomes of inbred individuals, can now be identified through genomic analysis, and provide greater power to detect inbreeding depression than traditional, pregenomic approaches. For example, endangered southern resident killer whales having more ROH were found to have reduced survival, with population models suggesting that this inbreeding depression has limited population growth. These findings help explain the population's lack of recovery despite efforts to reduce extrinsic environmental threats (*9*). Genomic analysis of inbreeding can also be useful in cases where detailed demographic data are unavailable, for example, to identify declining populations with particularly high inbreeding that might benefit from recovery actions such as genetic rescue.

Genome-scale data will continue to be scarce for at-risk species given the magnitude of the biodiversity crisis. It is therefore critical that genomic inferences are evaluated in the context of population genetic theory, to allow more confident extrapolation to cases where data are lacking (*10*). For example, studies that link genomic variation to fitness can inform the development and validation of more widely and rapidly applicable proxies of genetic health and viability in at-risk species (*11*). Finally, we caution against reliance on advanced interventions such as cloning and gene editing, which are unlikely to be broadly applied to listed species. Across the data-availability spectrum, ensuring the viability of species before they become critically imperiled is best supported by time-tested conservation biology principles: maintaining intact habitats sufficient for large, connected populations across species' ranges to ensure the integrity of ecological and evolutionary processes.

Fostering international conservation

By **Grethel Aguilar Rojas[6]** *and* **Nicholas A. Robinson[7]**

The ESA nationally, and the Convention on International Trade in Endangered Species (CITES) worldwide, protect species at risk of extinction. Created together, these laws are entwined and symbiotic. Sixty years ago, Congress sought to update the Lacey Act of 1900, which criminalizes trade in wildlife taken in violation of state or foreign laws. Meanwhile the International Union for Conservation of Nature (IUCN) was proposing a treaty to curb trade of species listed on IUCN's Red List of Threatened Species. In 1972, IUCN's experts testified in Congress to support enactment of an Endangered Species Act. The US Department of Interior supported IUCN's proposals for a new treaty. The US Department of State led negotiations of the "Washington Convention on International Trade in Endangered Species of Wild Fauna and Flora," which nations signed on 3 March 1973.

On 19 December 1973, the US House of Representatives and Senate both approved the ESA (*12*).

Under the ESA, the USFWS lists species as endangered or threatened regardless of the country in which the species lives. ESA fosters scientific collaboration worldwide to gather data for both ESA's listings and listings under CITES. ESA thus fosters international conservation of habitats and species. Governments know more is needed. When the United Nations Decade on Ecosystem Restoration sunsets in 2030, governments aim to have protected 30% of Earth's ecosystems. In September 2023, 83 nations signed a treaty to conserve marine biodiversity on the high seas. The 2022 Kunming-Montreal Framework of the Convention on Biological Diversity (CBD) sets targets for national action through 2030. In 2015, the US joined 193 nations at the UN endorsing Sustainable Development Goal 15 to halt biodiversity loss by 2030.

This path toward 2030 began in 1973. The ESA established the federal Management and Scientific Authorities that implement CITES. When all 184 nations in CITES confer annually, they expose anew the sixth mass extinction of species. Acknowledging that more than the ESA-CITES approach is needed, IUCN stimulated the negotiation of further treaties, such as the 1979 Convention on Migratory Species (*12*). Expanding on the ESA's ethical premises, IUCN proposed a normative basis for further action, which the UN General Assembly adopted as the 1982 "World Charter for Nature" (*12*). This Charter prescribes principles for protecting genetic viability, ecosystems, and population levels sufficient for survival of species. On the basis of these principles, in 1990 IUCN again proposed a new treaty, which the UN launched as the CBD at the 1992 "Earth Summit" in Rio de Janeiro (*12*). Ironically, controversies about the spotted owl, listed as threatened under the ESA, blocked US plans to sign the CBD in Rio. In 1993, the US did sign the CBD, but Congress has yet to ratify it.

The plight of biodiversity is grave. Success in 2030 and beyond will depend upon rekindling the spirit of 1973.

Assisted migration—moving species by translocation

By **Patrick D. Shirey**[8] *and* **Gary A. Lamberti**[9]

Assisted migration is the intentional translocation of species outside of their recent range to mitigate environmental change, which could include climate change, impaired watersheds, or altered land use (*13*). Perhaps the most famous translocation within the United States is the snail darter (delisted in 2022)—which was moved outside of its historic range in the 1970s to mitigate Tellico Dam construction in the darter's habitat. Other examples include the Virginia roundleaf birch (agencies propagated and distributed seedlings to botanical gardens after the population dwindled to 40 trees), and the Tennessee coneflower (nurseries and botanical gardens helped propagate the species to reduce risk to wild populations and supplement the wild populations). Though the basic science and logic behind translocation are straightforward, the scientific evidence to suggest whether it overall does more good than harm, and if good, then how best to do it, has been unsettled. This challenge has led to calls for controlled experiments with adequate planning and monitoring to be included in management plans for imperiled species (*14*).

In the Endangered Species Act of 1973, Congress did not restrict translocation as a management tool. However, in 1984, at a time when the Reagan administration was concerned about imperiled species potentially restricting private property development, the USFWS placed a restriction on translocations such that experimental populations could not be introduced outside of a probable historic range unless the primary habitat of the species has been unsuitably and irreversibly altered or destroyed [49 FR 33893, 50 CFR §17.81(a) 1984] (*15*). One management challenge under this restriction is that the regulations did not define unsuitable and irreversible habitat destruction. However, this regulatory restriction only applied to plant species occurring on federal or state land; privately owned plants did not have such restrictions against movement unless being sold in interstate commerce, opening the door for citizen-initiated assisted migration of listed, imperiled plant species (*16*).

In 2010, we suggested that the USFWS revisit the experimental population restrictions because assisted migration could be a viable management option albeit with risks (*15*). In 2023, the USFWS changed the regulation to eliminate the historic range restriction (88 FR 42642), noting that establishing populations outside of a historical range is necessary to avoid extinction for species such as the Florida Key deer threatened by climate change, and the Guam rail and Guam kingfisher (sihek) threatened by the invasive brown tree snake. Under the 2023 rule, the agencies must demonstrate that the experimental population will further conservation of the species, and must monitor possible adverse effects to the ecosystem that may result from the experimental population being established outside of its historical range.

Though the experimental population regulatory changes were sensible measures to improve tools available to agency biologists, the risks of assisted migration warrant a precautionary approach that requires detailed planning prior to coordinated assisted migration of a species. This detailed planning includes updating older recovery plans (*17*) and addressing the problem of chronically underfunded species recovery efforts (*18*).

Harnessing economics for effective implementation

By **Amy W. Ando**[10]

Though the ESA precludes the use of economic analysis in making listing decisions, insights and tools from economics have helped to make management and policy related to the ESA more successful and trigger sweeping changes in many human behaviors including logging, development, and water use. For example, economics research has informed efforts to reduce perverse habitat destruction incentives created by the original ESA and helped to quantify the impacts, costs, and benefits of ESA protections (*19*). Because natural resource economics has powerful tools (both analytical theory and numerical optimization) for optimizing policy and management in the face of trade-offs, uncertainty, and human behavior, this discipline can contribute yet more to biodiversity conservation under the ESA in a world where habitats are complex and changing.

Economists are working with ecologists and scholars of water management on strategies to help species in complex aquatic habitats (*20*). Joint management of water resources and aquatic species can help to minimize the cost of protecting species; for example, when planning dam removal to improve salmon habitat and migration, considering hydropower benefits can help decision-makers choose sites for removal that minimize the social costs. And efforts to regulate water use to protect in-stream flows for species need to be careful not to regulate only one type of water use when users can shift to deplete other sources instead. Also, bioeconomic research can inform strategies to save migratory species (*21*). New

Whooping cranes in South Dakota take off during spring migration. Economics research can inform strategies to ensure availability of habitat during migration.

policies such as "pop-up" habitat modification (like flooding of rice fields) or permeability improvement (like taking down fences) during times that migratory species are passing through can draw upon economics to optimize the timing, location, and extent of temporary actions to maximize their net benefits to society. Economists can also help to clarify how the net benefits of a migratory species vary over its range, helping to set the stage for regional negotiations that ensure a species' survival is in the best interests of people throughout its entire range. Conservation plans for all species must account for habitat shifts that are happening because of climate change; a conservation portfolio approach to reserve site planning can efficiently help to ensure that species have supportive environments in an uncertain future (*22*).

Economics can also help move beyond emergency measures to save species that are on the brink of extinction. Ongoing research can help ESA policy-makers and managers to enhance efforts and institutions that encourage private land owners to engage in preemptive conservation that avoids the need for endangered species listing at all (*23*). For example, successful preemptive conservation is more likely to occur if action is taken to help coordinate multiple private landowners to avoid free-rider problems and to prompt conservation before the species is so endangered that success of preemption is costly and unlikely. Economics can inform strategic thinking about management strategies and policies once a species has been recovered enough to be taken off the list (*24*). For example, differentiating population requirements for a species across the states in its range can reduce the ongoing costs of supporting the species' survival, and ancillary policies such as compensation for direct and indirect damages from a species like the gray wolf can reduce private incentives to eradicate them.

Pushing boundaries with new interventions

By **Stephen Palumbi**[11] *and* **Michael Wara**[12]

Protecting the literal foundation of tropical reef ecosystems requires new interventions that push the boundaries of historic implementation of the ESA and will require careful exercise of agency discretion under the Act. At the same time, preservation of reef ecosystems can be viewed as part of a decades-long effort to shift ESA protections from a focus on individuals to species to whole ecosystems within the confines of the statute.

Originally ESA protections for corals, as for other taxa, focused on the need to conserve particular species and their habitats. Rapid decline of coral reefs owing to climate change–driven heatwaves has led to global efforts in coral protection and calls to restore reefs by growing corals in coastal nurseries. Yet these efforts rarely result in fully restored reefs, and many nursery-grown corals succumb to rising temperatures. A new strategy is to restore reefs with naturally occurring corals that exhibit resistance to heat damage (*25*). Breeding corals in aquaculture facilities for higher heat resistance, and hybridizing them with more heat-resistant species, are also underway. In addition, engineering corals by changing their symbionts or microbiome or through gene editing has been proposed and proof-of-concept research conducted.

Two coral species are fully protected under endangered species rules, and more are listed as threatened. How might coral interventions affect the protection of corals under the ESA (*26*)? Protecting and increasing species numbers in lab or zoo settings is in line with the ESA, as is adding individuals from different natural populations to enhance population diversity or adaptation (*26*). Adding new species may be more of a gray zone because they may supplant native corals under ESA protection, and thus may constitute a "take" under ESA regulation and require interagency consultation and permitting.

Breeding corals for higher heat tolerance in the lab through artificial selection may be similar to efforts to breed black-footed ferrets for disease resistance (*27*), a project underway with USFWS approval (though release of these animals has not happened yet). The van Oppen team in Australia took internal symbionts from corals into the lab (*28*) and evolved them over 10 years to be more resistant to high heat. They stripped corals of their regular symbionts and substituted the lab-evolved strains. A few colonies successfully integrated the lab-evolved symbionts and grew well under higher-temperature conditions. ESA protections currently regulate "infecting" endangered corals with manipulated symbionts, as well as placing them back out into the field (*26*).

Probably the most technically challenging of the possible interventions involves genetically engineering corals. Cleves and

PHOTO: GERRIT VYN/NPL/MINDEN PICTURES

colleagues (*29*) took a CRISPR injection rig to Australia for the few nights of coral spawning each year and injected thousands of eggs. Yet, such corals are not currently permitted to be released into the wild, and at this point there is no clear understanding of the genes that need to be altered to generate climate-resistant corals. In this case, if genes in the wild are found that confer climate protection, they can be used under the ESA. But creating those genes—even if it were possible—appears to be outside current ESA guidelines.

Both the environmental harm to corals and new approaches to saving coral reefs are advancing at an accelerating pace. For most of these interventions, permits for research or enhancement, incidental take, or interagency consultation mechanisms are built into the ESA system and can and should allow exploration of these new possibilities. An important opportunity for facilitating new conservation approaches could be the development of recovery plans for 15 Indo-Pacific coral species (*30*).

Many mechanisms within the ESA balance between protection and enhancement of populations. For the last half-century, the ESA has been fundamental in protecting species as they existed in the past. Attention must turn to adapting its implementation to preserve ecosystems for the future.

Learning to overcome barriers to adaptive management

By **Mark W. Schwartz[13]** *and* **Matthew A. Williamson[14]**

A core challenge for public agencies responsible for ESA implementation and enforcement is to clearly demonstrate success so as to be recognized by society as providing legitimate, effective governance. To be sure, species are recovering under the ESA. But how recovery funding drives that recovery is unclear. The USFWS has a ranking system to prioritize species, but recovery funding is poorly correlated with priority rank. Recovery plan actions for species are ranked, but to little effect. In addition, although federal agencies have adopted Adaptive Management, little effort is allocated to monitoring outcomes of actions (*31*).

Effectiveness and legitimacy of the ESA are fostered through transparency and clear links between expenditures, actions, and outcomes. Over the past 20 years, drawing on advances in decision science and computational algorithms, conservation practice has created a variety of frameworks for planning, decision-making, spatial prioritization, evidence use, and outcome evaluation (*32*). Despite demonstrated successes (*33*), use of these frameworks to manage federally listed endangered species remains the exception. Accelerating the recovery of endangered species requires increasing the capacity to coordinate and efficiently invest in priority actions targeted to specific objectives combined with monitoring, learning, reporting, and adjusting future actions (*31*).

If the ESA is to truly deliver on recovering endangered species, with strong credibility among the public, then an explicit, transparent rationale for resource allocation to achieve recovery objectives is vital. Recently revised public recovery documentation (Species Status Assessments, Recovery Plans, Recovery Implementation Strategy, and Implementation Action Tables) have improved planning and action tracking but fail to explicitly link actions to expected outcomes. Adaptive management is most effective when plans rest on a conceptual model that links actions to recovery objectives through some theory of change (*34*).

There are several barriers to strategic adaptive management of endangered species. First, and foremost, is that the lead ESA agencies, tasked with recovery planning and tracking, are minority financial contributors to recovery actions. In fiscal year 2020, for example, just 8.4% of the $1.25 billion of public funding spent on endangered species came from the USFWS. As a consequence, the USFWS plans, prioritizes, and tracks actions that are almost entirely not their own. With just a small fraction of the funds, the USFWS has limited capacity to direct resources to priority species, a situation exacerbated by congressional earmarks for special interest species. Within species, the USFWS not only lacks the capacity to direct funds, but uses a three-tiered priority rank that is not driven by decision tools to optimize outcomes.

Lacking the required financial resources to fully implement recovery actions, public agencies make difficult choices in funding actions, and critical monitoring and evaluation functions appear frequently left out. Inadequate monitoring and evaluation not only undermine the ability of agencies to justify their actions to the public, but also forego efficiencies to be gained through learning and improving. Better cross-agency coordination and collaboration is needed to make optimal use of limited resources and implement adaptive management. Interventions on behalf of endangered species are experiments from which we must learn (*35*).

Sustainable, trustworthy, human-technology partnership

By **Tanya Berger-Wolf[15,16], Sara Beery[17], David Rolnick[18,19], Justin Kitzes[20], David Thau[21], Devis Tuia[22], Daniel Rubenstein[23]**

Despite conservation successes, we are in the middle of a mass extinction without even knowing all that we are losing and how fast. To address the urgency and scale of these challenges, there has been an explosion of technology developed to collect data on biodiversity, and parallel advances of computational methods in data analysis, machine learning (ML), artificial intelligence (AI), and cyberinfrastructure. The goal is to fill the data gap and turn raw data into high-resolution information about living organisms, enabling scientific inquiry, conservation, and policy decisions (*36*).

For example, the National Oceanic and Atmospheric Administra-

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A field biologist adds scent to the ground to encourage animals to stop in front of a trail camera, a technology increasingly used to survey animal species.

tion (NOAA) Advanced Sampling and Technology for Extinction Risk Reduction and Recovery (ASTER3) (*37*) program for fisheries' conservation uses aerial and submersible drones, acoustic sensors, satellite- and drone-based imaging, -omics, and AI/ML. The USFWS uses ML to track and count bird populations from aerial images, while the Bureau of Ocean and Energy Management tracks and counts whales using algorithms to identify individuals in photographs (*38*). States use motion-sensitive cameras and an ML image object detector (*39*) to survey animal species, and smartphone-enabled citizen scientists count insects, identify bird songs, and report millions of plant observations (*40*). Algorithms developed for deploying US Federal Air Marshals are now used to plan park rangers' routes and deter wildlife criminals (*41*). Techniques for planning robot paths are leveraged to prioritize areas for biodiversity conservation (*42*).

The technological shift has the potential to enable a more effective, affordable, highly automated, globally distributed, locally relevant, real-time biodiversity monitoring system, improving equity across taxa as well as geographic regions (*43*). Technology can change the scale of conservation efforts by expanding our understanding of habitats and communities and predicting how they might change under different protection plans.

Yet, technology comes with risks. The collected data are biased, missing large areas and many taxonomic groups. Lack of robust collaborations between conservation biologists and computational and AI experts slows the development of computational tools. Biased data and methods will distort evaluation and discovery. If not carefully used, relying on technology for nature observation can also distance humans from nature, severing an important personal connection needed to inspire the next generation of scientists and nature lovers.

Technology is expensive, and conservation is already underfunded, leading to inequities in access to tools, data, and computational resources, as well as the expertise needed to use them. Technology pulls funding away from other needs, not always with commensurate impact, with the focus too often on using technology for its own sake. Conservation needs buy-in and support from local communities who are directly affected by nature loss. However, technology can undermine community or individual data rights or be deployed in languages or with cultural norms not relevant locally. But when local communities are given agency in every part of the process, trusting and productive partnerships can be developed.

The same technologies that accelerate impact can also accelerate environmental and conservation risks. Computation can be energy and water intensive, and computing hardware uses rare metals and produces e-waste. Additionally, AI-enabled data-gathering tools may be used by nature criminals, and are already used extensively to aid oil and gas extraction.

To be useful, technology needs to be a sustainable and trustworthy partner. Ultimately, technology alone, even AI, will not save the planet's species. But neither will humans alone. Human and machine partnership for conservation is our best chance for success.

Adding tribal experience and removing inequity

By **Caleb R. Hickman[24]** *and* **Julie Thorstenson[25]**

Over millennia, tribes have learned to coexist with species on the American continent. Despite centuries of conflict with settler-colonial Americans, federally recognized tribes influence the management of nearly 140 million acres in the US. These lands feature diverse legal classifications offering protective status with regulatory burdens specific to tribes (*44*). Studies underscore the pivotal role of Indigenous stewardship, revealing higher biodiversity levels and more borders with protected areas compared to adjacent state lands (*44*). Indigenous-managed lands constitute only 2.6% of the US but overlap with 12% of Key Biodiversity Areas, underscoring their ecological importance (*44*).

Despite their crucial conservation role, tribes face considerable funding disparities compared to states. Tribes miss out on the annual federal aid of more than $1 billion allocated to states for conservation under the Wildlife Restoration Act (Pittman-Robertson) and the Sport Fish Restoration Act (Dingell-Johnson). In addition, the State Wildlife Grant (SWG) program, distributed on the basis of species and land area (which often lumps in tribal lands), allocated $1.2 billion over 20 years for nongame species conservation to every state. Tribes do not receive the SWG funds, but a similar fund for tribes is the extremely limited Tribal Wildlife Grant (TWG) program. The TWG program, funded with

The Shoshone-Bannock Tribes have worked to protect and restore the Snake River and endangered sockeye salmon.

competitive awards and capped at $200,000 per project, has disbursed $105.6 million since 2002, yet only 25% of applications received funding (*44*). This results in capacity challenges, whereby tribes must juggle all taxa management (among other natural resources) while state agencies can hire specialized biological staff that focus on single taxon groups, and single species. Insufficient funds result in reduced conservation efforts, management sovereignty, and tribal lifeways.

Tribally held priorities can be overlooked when applying the ESA. We recommend applying Indigenous perspectives to the ESA as a way to avoid neocolonial American practices. Lamb *et al.* (*45*) recommend integrating food security and cultural relationships into species recovery plans. We see a need to revitalize traditional coexistence philosophies (*46*) while avoiding the "Ecological Indian" fallacy that overromanticizes the role of Indigenous people as historical stewards rather than modern practitioners (*47*). Without Indigenous coexistence philosophy in modern management, neocolonial influences may lead tribes to embrace market trade and industrial capitalism (*3*). Despite inquiries about the "in vogue" traditional ecological knowledge, tribes' philosophies often remain overlooked without direct federal oversight, which is an all too often paternalistic approach (*48*).

To achieve true species recovery for all, a shift in conservation philosophy is essential (*46*). Tribes, as sovereign nations, face a disproportionate burden compared to US citizen states, which is antithetical to the Secretarial Order 3206 that emphasizes cultural deference. A recent inclusive step occurred when President Biden's administration supported a memorandum on Tribal Consultation, which can include species conservation.

By recognizing the distinct challenges that tribes face, the scientific community can also play a vital role in reframing the ESA into a law for everyone. This equity can be realized when a coproduced form of conservation includes tribal knowledge systems and priorities from the beginning and shares resources throughout the process (*48*).

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Genome editing and deliberate extinction

By **Gregory E. Kaebnick[26], James P. Collins[27], Athmeya Jayaram[26]**

Advancing genome editing technologies, prominent among them synthetic gene drive systems, may lead to methods for suppressing or locally exterminating some species, or even driving them extinct. How that prospect accords with the ESA is an emerging policy issue with potentially profound ramifications for environmental, public health, and agricultural policy.

Effects of a gene drive system would depend on the design of the system, e.g., alleles targeted for change, diversity of a species' gene pool, and a species' population structure (*49*). For example, a drive that reduced female fertility in malaria-transmitting mosquitoes *Anopheles gambiae* could lead to substantial population decline on a regional scale, though modeling suggests that complete extinction is unlikely (*50*). Gene drive systems are also in development to eliminate invasive rodent populations that threaten other species on oceanic islands (*51*). Other candidate species include the New World screwworm, a blow fly causing considerable damage to livestock and posing a threat to humans, for which genes required for female development or fertility have been identified and could be targeted by gene drive (*52*).

Eliminating disease-carrying mosquitoes and screwworm appears to be permissible under the ESA, which exempts insect pest species that present "an overwhelming and overriding risk" to humans. The law's applicability to a widespread population decline of invasive rodent populations due to a gene-drive system is more ambiguous. ESA protections apply only after a species is listed as endangered, which typically requires evidence that the species has already declined. The ESA, therefore, may not apply to the prospective threat of a gene drive (*53*). Additionally, how genome editing would be considered in the listing process is not settled. The factors that trigger listing have generally been external threats to a species such as hunting and habitat change, not genetic alterations integrated into a species' gene pool.

But if the letter of the law needs clarification, the spirit of the ESA clearly places an extremely high value on species and rules out eradication in most cases. The exception made for insect pests shows, however, that some goals, such as preventing the enormous public health harms associated with some insects, might override that high value. Exactly which harms are overriding—and whether they are posed only by insects—are important questions. But, plainly, if the ESA is taken to heart, genetic interventions that could lead to a species' extinction should be evaluated very conservatively and would be acceptable only rarely.

Regulating trade toward global sustainable development

By **Thomas Deleuil**[28] *and* **Ying Zhao**[28]

A group of scientists and environmental managers in 1963 called for "an international convention on regulation of export, transit and import of rare or threatened wildlife species or their skins and trophies" as enshrined in a resolution of the IUCN (*54*). In 1973, based on a recommendation of the 1972 Stockholm Conference on the Human Environment, the United States hosted a Plenipotentiary Conference in Washington, DC, where the CITES was opened for signature. The US was the first signatory country to ratify the Convention, which came into force in 1975 (*55*).

CITES is an international legally binding agreement regulating billions of dollars of international trade in specimens of wild animals and plants. The two cardinal rules are that trade shall not be detrimental to the survival of the species and traded specimens must have been acquired legally (*56*).

Parties are required to adopt domestic legislation to ensure full implementation of CITES at the national level. In the US, the ESA is the domestic legislation for CITES. The USFWS acts as both the Management Authority and Scientific Authority for CITES, tasked with providing scientific advice, verifying the legality of specimens traded, issuing CITES permits and certificates, enforcing pertinent laws, and submitting trade reports, for example (*57*).

The ESA not only encompasses US international obligations under CITES but also imposes, in some cases, stricter domestic measures above CITES standards, including the protection of species that are not covered by the Convention. For instance, the ESA mandates the development of recovery plans for the conservation and survival of listed species when deemed necessary (*56*). Thus, the ESA also demonstrates the commitment of the US to the conservation of species.

Today, CITES has 184 signatory Parties and regulates trade in over 40,900 species. It is one of the most successful international environmental treaties concerned with nature conservation. Notably, no species listed under CITES has become extinct, and the US—through ESA—has played its part in this global effort. However, since the adoption of the Convention in 1973, societies have evolved and environmental threats have multiplied. Through ESA, the USFWS, Office of Law Enforcement, has also played and continues to play an important role in combating illegal wildlife trade, including online trade (*58*).

The pressure to regulate trade in and conservation of wild species is growing. In an increasingly complex world, as both CITES and ESA mark their 50th anniversaries, they are more relevant than ever to ensure that wild species are conserved for the benefit of people, planet, and prosperity to achieve the United Nations Sustainable Development Goals.

REFERENCES AND NOTES

1. D. Lueck, J. A. Michael, *J. Law Econ.* **46**, 27 (2003).
2. J. A. Smith, K. Brust, J. Skelton, J. R. Walters, *Condor* **120**, 223 (2018).
3. T. Dietz, E. Ostrom, P. C. Stern, *Science* **302**, 1907 (2003).
4. R. L. Fischman, V. J. Merestsky, M. P. Casteilli, *Yale J. Regul.* **38**, 976 (2021).
5. R. L. Fischman, J. B. Ruhl, *Conserv. Biol.* **30**, 268 (2016).
6. B. Forester, T. Lama, "The role of genomics in the future of ESA decision-making" in *The Codex of the Endangered Species Act, Volume II, The Next Fifty Years*, L. E. Baier, J. F. Organ, Eds. (Rowman and Littlefield, 2023), pp. 159–186.
7. W. C. Funk, B. R. Forester, S. J. Converse, C. Darst, S. Morey, *Conserv. Genet.* **20**, 115 (2019).
8. R. S. Waples *et al.*, *J. Hered.* **113**, 121 (2022).
9. M. Kardos *et al.*, *Nat. Ecol. Evol.* **7**, 675 (2023).
10. M. Kardos, *Proc. Natl. Acad. Sci. U.S.A.* **120**, e2316880120 (2023).
11. S. Hoban *et al.*, *Conserv. Lett.* **16**, e12953 (2023).
12. J. Barbara, Lausche, Weaving a Web of Environmental Law, Chapter 6, "The Making of CITES" (2008); https://www.iucnael.org/en/academy-publications/7-weaving-a-web-of-environmental-law.
13. J. S. McLachlan, J. J. Hellmann, M. W. Schwartz, *Conserv. Biol.* **21**, 297 (2007).
14. C. Sáenz-Romero *et al.*, *Can. J. For. Res.* **50**, 843 (2020).
15. P. D. Shirey, G. A. Lamberti, *Conserv. Lett.* **3**, 45 (2010).
16. P. D. Shirey, B. N. Kunycky, D. T. Chaloner, M. A. Brueseke, G. A. Lamberti, *Conserv. Lett.* **6**, 300 (2013).
17. P. D. Shirey, S. A. R. Colvin, L. H. Roulson, T. E. Bigford, *Fisheries* **47**, 256 (2022).
18. P. D. Shirey, S. A. R. Colvin, *Fisheries* **47**, 299 (2022).
19. C. Langpap, J. Kerkvliet, J. F. Shogren, *Rev. Environ. Econ. Policy* **12**, 69 (2018).
20. K. Kroetz, Y. Kuwayama, C. Vexler, *Rev. Environ. Econ. Policy* **14**, 194 (2020).
21. H. J. Albers *et al.*, *Rev. Environ. Econ. Policy* **17**, 111 (2023).
22. A. W. Ando, M. L. Mallory, *Proc. Natl. Acad. Sci. U.S.A.* **109**, 6484 (2012).
23. T. Treakle, R. Epanchin-Niell, G. D. Iacona, *Conserv. Biol.* **37**, e14104 (2023).
24. C. Sims, D. Aadland, D. Finnoff, J. Hochard, *Ecol. Econ.* **174**, 106656 (2020).
25. B. Cornwell *et al.*, *eLife* **10**, e64790 (2021).
26. NOAA Fisheries, Endangered Species Act Legal and Policy Review of Interventions to Increase the Persistence and Resilience of Coral Reefs (2020); https://www.fisheries.noaa.gov/resource/document/endangered-species-act-legal-and-policy-review-interventions-increase-persistence.
27. R. L. Sandler, L. Moses, S. M. Wisely, *Biol. Conserv.* **257**, 109118 (2021).
28. W. Y. Chan, L. Meyers, D. Rudd, S. H. Topa, M. J. van Oppen, *Glob. Change Biol.* **29**, 6945 (2023).
29. P. A. Cleves *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **117**, 28899 (2020).
30. NOAA Fisheries, 15 Indo-Pacific Coral Species Recovery Outline; https://www.fisheries.noaa.gov/resource/document/15-indo-pacific-coral-species-recovery-outline.
31. M. Evansen, A. Carter, J. Malcom, *Environ. Res. Lett.* **16**, 031001 (2021).
32. M. W. Schwartz *et al.*, *Conserv. Lett.* **11**, e12385 (2018).
33. B. G. Marcot, J. E. Lyons, D. C. Elbert, L. Todd, *Animals* **11**, 569 (2021).
34. L. A. Dietz, M. Brown, V. Swaminathan, *Am. J. Primatol.* **72**, 425 (2010).
35. P. J. Ferraro *et al.*, *Science* **381**, 735 (2023).
36. D. Tuia *et al.*, *Nat. Commun.* **13**, 792 (2022).
37. National Oceanic and Atmospheric Administration (NOAA) Fisheries, "Advanced Sampling and Technology for Extinction Risk Reduction and Recovery"; https://www.fisheries.noaa.gov/endangered-species-conservation/advanced-sampling-and-technology-extinction-risk-reduction-and.
38. D. Blount *et al.*, *Mamm. Biol.* **102**, 1005 (2022).
39. S. Beery, D. Morris, S. Yang, arXiv:1907.06772 (2019).
40. D. Fraisl *et al.*, *Nat. Rev. Methods Primers* **2**, 64 (2022).
41. F. Fang *et al.*, *Proc. AAAI Conf. Artif. Intell.* **30**, 3966 (2016).
42. D. Silvestro, S. Goria, T. Sterner, A. Antonelli, *Nat. Sustain.* **5**, 415 (2022).
43. GPAI, *Biodiversity & Artificial Intelligence, Opportunities and Recommendations, Report* (Global Partnership on AI, 2022).
44. J. Thorstenson, "Diversity and Complexity of Tribal Fish and Wildlife Programs" in *Wildlife Stewardship on Tribal Lands. Our Place Is in Our Soul*, S. Hoagland, S. Albert, Eds. (Johns Hopkins Univ. Press, 2023), pp. 12–21.
45. C. T. Lamb *et al.*, *Science* **380**, 694 (2023).
46. K. Anker, "Ecological jurisprudence and Indigenous relational ontologies Beyond the 'ecological Indian'?" in *From Environmental to Ecological Law*, K. Anker, P. D. Burdon, G. Garver, M. Maloney, C. Sbert, Eds. (Routledge, 2021), pp. 104–118.
47. S. Krech III, *Ecological Indian: Myth and History* (Norton, 1999).
48. C. R. Hickman, J. Thorstenson, A. Carlisle, S. J. Hoagland, S. Albert, "Research with Tribes: A Suggested Framework for the Co-Production of Knowledge" in *Wildlife Stewardship on Tribal Lands. Our Place*
49. NASEM, *Gene Drives on the Horizon: Advancing Science, Navigating Uncertainty, and Aligning Research with Public Values* (NASEM, 2016).
50. A. R. North, A. Burt, H. C. J. Godfray, *BMC Biol.* **18**, 98 (2020).
51. A. Birand *et al.*, *Mol. Ecol.* **31**, 1907 (2022).
52. M. J. Scott *et al.*, *Commun. Biol.* **3**, 424 (2020).
53. J. Monast, *North Carol. Law Rev.* **97**, 1329 (2019).
54. CITES, Official Newsletter of the Parties, Special Edition, 3 March 2003 – 30th Anniversary; https://cites.org/sites/default/files/eng/news/world/30special.pdf.
55. CITES, List of Contracting Parties: https://cites.org/eng/disc/parties/chronolo.php.
56. CITES Articles II, III, IV and V. See also, inter alia: P. A. Sheikh, E. H. Ward, The Endangered Species Act: Overview and Implementation. Congressional Research Service, 23 and 47-48 (4 March 2021); http://crsreports.congress.gov/product/pdf/R/R46677.
57. C. D. Daniel, Evaluating, *William Mary Environ Law Policy Rev.* **23**, 683 (1999).
58. CITES, Official Newsletter of the Parties, Issue 19; https://cites.org/eng/news/world/19/4.php.

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