Title

Committed genetic erosion: parallels from climate science for proactive conservation

Running title

Committed genetic erosion and climate parallels

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Abstract

While climate science recognises that past emissions lock in future impacts ("committed climate change"), the idea of lagged losses is less embedded in biodiversity policy. This is particularly true for genetic diversity loss (genetic erosion), the least visible dimension of the biodiversity crisis. To highlight this risk, we introduce the term "committed genetic erosion": future losses set in motion by past habitat loss, fragmentation, and population decline. Using parallels from climate science, we develop four arguments for biodiversity policy: genetic diversity loss is already widespread; biological inertia locks in further loss under business as usual; indicators and forecasting tools can quantify risk and project trajectories; and proactive interventions are more effective than reactive responses or speculative technological fixes. Critically, genetic inertia operates locally, providing a tractable window for restoring connectivity, maintaining viable effective population sizes, and well-planned genetic rescue. Acting now will safeguard the adaptive potential that underpins biodiversity resilience.

Keywords

Genetic diversity, extinction debt, genetic rescue, Global Biodiversity Framework, tipping points

Introduction: Biodiversity and climate, two interlinked crises

A rapidly changing world is increasing the need for resilient species that can adapt to new environments. Climate change and biosphere integrity, encompassing genetic diversity, are recognised as key dimensions of planetary stability, and current trends indicate that both are operating beyond safe limits for humanity (Richardson et al. 2023). Genetic diversity provides the foundation for adaptive capacity, enabling species and the ecosystems they comprise to persist through change. Yet despite being highlighted for decades (Frankel 1974), genetic diversity remains the least visible dimension in biodiversity policy and public discourse, and is the domain most recently integrated into global biodiversity frameworks. For example, the United Nations (UN) Convention on Biological Diversity (CBD) Kunming-Montreal Global Biodiversity Framework (GBF) now explicitly includes maintaining the adaptive potential of all species' populations as part of its goals and targets (Convention on Biological Diversity 2022), marking unprecedented political recognition of genetic processes in nature.

Recognition of the importance of genetic diversity has come after decades of addressing global environmental change through separate climate and biodiversity agendas (Pettorelli et al. 2021, Richardson et al. 2023). The UN CBD and the UN Framework Convention on Climate Change (UNFCCC) were signed in 1992 as sister conventions (ratified in 1993 and 1994, respectively, ipbes.net). Yet, their trajectories have diverged. The UNFCCC gained momentum through strong scientific leadership (e.g., Bolin 1991) and a clear global narrative shaped by the Intergovernmental Panel on Climate Change (IPCC). In contrast, scientific input into biodiversity policy evolved more slowly through the CBD Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA; Koetz et al. 2008; Laikre et al. 2008), and later through the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES;

established 2012, first global assessment 2019), which has broadened the information available to the CBD. This imbalance has contributed to less public attention and weaker implementation of biodiversity policy than of climate policy (Mace et al. 2018, Pörtner et al. 2021). Today, calls to enhance coherence among these frameworks, and recent collaborations between IPBES and the IPCC, signal renewed recognition that the solutions to climate and biodiversity loss are inseparable (Pörtner et al. 2021, IPBES 2024).

Climate science offers important lessons for biodiversity policy, including the mechanistic concept of commitment: the idea that past emissions and the inertia of the Earth system predetermine aspects of future change. This does not mean that global temperature will keep rising indefinitely if emissions cease; rather, it refers to impacts already locked in by past warming, such as ongoing sea level rise, ice-sheet melt, and thawing permafrost (Schuur et al. 2015, IPCC 2023, Abram et al. 2025). Components of the climate system are also thought to include critical thresholds that, if breached, would trigger large, irreversible changes (Armstrong McKay et al. 2022). Whether "committed climate change" will force the Earth system beyond these tipping points is the subject of intense concern and scholarship (Steffen et al. 2018).

A clear parallel exists for biodiversity. Habitat loss, fragmentation, and over-exploitation have driven elevated extinction rates and reduced many remaining species to small, isolated populations (Pimm et al. 2014, Ralls et al. 2018). Persistent small population sizes set in motion an extinction vortex: a reinforcing cycle of genetic loss and population decline (Figure 1; Gilpin and Soulé 1986). In this feedback loop, stochastic effects (genetic drift) and inbreeding can result in an accumulation of harmful mutations and lowered individual reproductive fitness and survival (inbreeding depression), in turn driving further declines in population size. Genetic diversity can continue to erode even after threats are mitigated or population numbers appear stable (Figure 1 –

maintenance trajectory; Gargiulo et al. 2025; Pinto et al. 2024). Indeed, even if a population grows in size, some life-history traits (e.g., long generation length) create biological inertia, producing a lag in which past impacts continue to define the future state of populations long after disturbance (Kurland et al. 2023, Gargiulo et al. 2025). Over generations, these processes can intensify, leading to irreversible loss of genetic variation and, ultimately, species extinction (Frankham et al. 2017). This "genetic extinction debt" represents the first stage of a broader extinction trajectory, reflecting similar time-lagged dynamics that underlie "extinction debt": situations in which species are likely to go extinct in the future because environmental conditions can no longer support long-term persistence (Tilman et al. 1994, Hanski and Ovaskainen 2002).

The concept of committed climate change has mobilised consensus and action by underscoring a critical insight: delayed action locks in future impacts. Therefore, to motivate policy discussions and communicate urgency in the biodiversity sphere, we propose the term "committed genetic erosion" to describe the future loss of genetic diversity already set in motion by past demographic and landscape change. Like committed climate change, committed genetic erosion arises from inertia and time lags, rather than inevitable global outcomes (Gargiulo et al. 2025); however, it differs from the climate concept in two critical respects. Climate inertia locks in regional to global impacts that are largely irreversible on human timescales (King et al. 2024, Perkins-Kirkpatrick et al. 2025), whereas genetic inertia operates at the local scale and can, to a certain degree, still be altered through timely intervention (Box 1). These attributes offer a window of opportunity: targeted interventions can often attenuate the realisation of committed genetic erosion. In this sense, the outcomes of ambitious action for biodiversity can be more immediate and tangible than in climate systems. This tractability is a strategic advantage that conservation policy and planning must now embrace.

Here we use climate science as a scaffold to re-frame conservation of genetic diversity and explore the idea of committed genetic erosion through four parallels: (1) multiple lines of evidence show change is already occurring; (2) time lags mean that further change is committed under business as usual; (3) we can measure, track, and forecast risk to guide early action; and (4) proactive measures are needed that address root causes. The need for action is supported by strong evidence, broad consensus, and increasingly sobering predictions for the future (Hoban et al. 2021, Exposito-Alonso et al. 2022, Gargiulo et al. 2025, Shaw et al. 2025). Business as usual, primarily reactive conservation (acting only after loss is observed; Figure 1), could lead to a future of ongoing genetic loss that cascades into species extinction, triggering broader biodiversity collapse. By recognising the scale of this challenge and the importance of early action, we hope to catalyse the long-called-for paradigm shift in conservation practice (Ralls et al. 2018), placing genetic diversity at the core of biodiversity conservation strategies.

Parallel 1: Change is happening now

Human-caused climate change is now undeniable. Human activities have unequivocally warmed the planet, with the long-term global surface temperature trend now estimated at 1.34–1.41 °C above the 1850–1900 baseline (WMO 2025). Continued greenhouse gas emissions are driving widespread and rapid changes across the atmosphere, ocean, cryosphere, and biosphere, and climate change is influencing weather and climate extremes in every region of the world (IPCC 2023).

Like climate change, multiple lines of evidence show that major genetic erosion of species is underway. This is true for a wide range of taxa and regions, even over just a few generations, and even for species not currently considered threatened (Schmidt et al. 2023, Mastretta-Yanes et al. 2024, Shaw et al. 2025). This trend aligns with recent studies on North American birds and mammals (Schmidt et al. 2020), global plant populations (González et al. 2020), and global predictions suggesting more than 10 % of genetic diversity may already be lost (Exposito-Alonso et al. 2022). The widespread signal of genetic erosion, even over short time frames, suggests that substantial population size declines are driving this loss.

Shaw et al. (2025) found that genetic diversity loss was most pronounced where land use change, disease, abiotic disturbances (e.g., wildfire, floods), and harvesting or harassment (e.g., hunting, logging, stressing) occurred. Many species now persist in small, fragmented populations (Frankham 2022). These conditions are expected to erode genome-wide diversity and increase inbreeding (Soulé 1980); predictions well-supported by experimental data (Rich et al. 1979, Montgomery et al. 2000), and real-world observations (e.g., Figure 2; Hoelzel et al. 2024; Ralls et al. 2018). A recent global assessment of genetic indicators across 5,271 populations also found that while the majority of species maintain most of their historic populations (for now), for 58 % of species assessed, all populations were too small to sustain genetic diversity over time; thus reducing their adaptive capacity (Mastretta-Yanes et al. 2024). Massive population losses could follow in the near-term, even triggering extinction vortices for many taxa (Figure 1; Gilpin and Soulé 1986).

Human-induced changes can create conditions for rapid evolutionary responses (IPBES 2019), but the capacity for such adaptation depends largely on existing (standing) genetic variation (Allendorf et al. 2024, Mergeay 2024). The kelp (*Ecklonia radiata*) forests of Western Australia, where the interdisciplinary study of marine heatwaves emerged (e.g., Hobday et al. 2016), provides a well-documented example. In 2011, a marine heatwave caused widespread kelp canopy loss. Populations with higher genetic diversity were more likely to persist through the event, while low-diversity stands collapsed (Wernberg et al. 2018). In the following years, recovery was aided by recolonisation from nearby forests, with high connectivity enabling the gene flow needed to maintain diversity and support adaptation to warming conditions (Vranken et al. 2025). These studies show that genetic diversity and gene flow are essential for persistence and resilience under accelerating change. Genetic diversity thus comprises the within-species component of "response diversity", a key aspect of ecological resilience that reflects the capacity of populations to respond differently to environmental change (Nadeau and Urban 2019, Walker et al. 2023). Managing diversity and connectivity is central to maintaining such flexibility and is a cornerstone of "resilience thinking" in ecosystem management (Biggs et al. 2012). Thus, conserving genetic diversity is fundamental to conserving species and ecosystems, and ensuring their long-term resilience (Figure 1). Because the recovery of diversity through mutation often requires hundreds or thousands of generations (Lande and Barrowclough 1987), preventing genetic erosion is critical (Figure 2).

Parallel 2: Change will continue under business as usual

Many human-driven climate change impacts are locked in for decades to millennia, even under rapid emissions reduction scenarios (Abrams et al. 2023, IPCC 2023). Because of the thermal inertia of the climate system, global temperatures are expected to continue rising for several decades even if greenhouse gas concentrations were stabilised today (Abrams et al. 2023). Some scenarios even involve a temporary "overshoot", where temperatures exceed 1.5–2 °C before later declining through mitigation, yet many ecosystems will not return to their prior states once thresholds are crossed (Armstrong McKay et al. 2022, Abrams et al. 2023). Under current national commitments (business as usual), critical thresholds for several major tipping elements are likely to be crossed this century, including the loss of Greenland and West Antarctic ice sheets, the Amazon rainforest, permafrost carbon stores, and tropical coral reefs (Steffen et al. 2018, Armstrong McKay et al. 2022, Abrams et al. 2023, IPCC 2023, Abram et al. 2025). Once these thresholds are transgressed, self-reinforcing feedbacks could drive cascading and irreversible impacts (Schuur et al. 2015, Armstrong McKay et al. 2022, IPCC 2023, Wunderling et al. 2023).

Similar lagged responses also occur in biological systems, including in population-level genetic processes. The effective population size (Ne) is the genetic analogue of census size (Nc); where Nc shapes the ecological dynamics of a population, Ne captures its evolutionary dimensions, determining the strength of genetic drift and the resulting rates of inbreeding accumulation and genetic diversity loss (Waples 2025). Theoretical models predict that the time it takes for genetic diversity loss to manifest fully after a demographic decline is on the order of 2Ne generations (Crow and Aoki 1984). For many populations and species, this corresponds to hundreds to thousands of generations. This means that genetic erosion may go undetected long after populations begin to decline, potentially giving the false impression that genetic diversity is stable (Lande 1988). Global genetic diversity losses of 13–22 % have been estimated relative to recent baselines, and long-term losses are forecast to reach 42–48 % even if population numbers stabilise, with greater losses under high habitat fragmentation (Mualim et al. 2025 [preprint] doi:10.1101/2024.10.21.619096).

Species with large populations and broad distributions can hold a reservoir of genetic diversity that masks local losses, and seed banks and dormant life stages can retain genetic signatures of past conditions (Plue et al. 2017, Staude et al. 2020). For example, genetic diversity was apparently maintained over time in taxa with historically large and/or widely distributed populations, such as insects (including bees and flies), ray-finned fishes (pelagic and migratory), and dicotyledonous plants (Shaw et al. 2025). But these groups may still be at risk - now or in the future - if large demographic changes occur. Similarly, in long-lived species, even substantial risk of genetic erosion may not be detectable over relatively short-term sampling periods (Gargiulo et al. 2025), potentially leading to underestimates of extinction risk.

These lagged genetic responses mirror climate dynamics, where gradual change can culminate in abrupt, often irreversible shifts. As resilience declines, stressors may tip an already vulnerable system into collapse. For example, long-term climatic “presses” (e.g., gradual warming or drying) interacting with short-term “pulses” (e.g., droughts or fires) can trigger abrupt transitions, as seen in population collapses and regime shifts worldwide (Biggs et al. 2018, Harris et al. 2018). Similar dynamics may have contributed to the extinction of the woolly mammoth (*Mammuthus primigenius*) on Wrangel Island, which lacked human occupation (Dehasque et al. 2024). Ancient DNA revealed a severe population bottleneck followed by demographic recovery, but eventual collapse. Hundreds of generations of inbreeding and the accumulation of mildly deleterious mutations may have left the population close to a tipping point (Dehasque et al. 2024). Such processes also occur in agriculture, where selective breeding reduces genetic diversity and heightens disease vulnerability, as seen in the devastating effects of southern corn leaf blight on maize in the USA (Strange and Scott 2005).

The consequences of genetic erosion can also feed back into, and exacerbate, climate and ecosystem processes. Increasing evidence shows that transgressing key planetary boundaries, whether related to climate change or to the wider biosphere, can amplify risks across domains

(Richardson et al. 2023). Genetic diversity is a key component of biosphere function, and its erosion can weaken both ecological and climate resilience. For example, black spruce (*Picea mariana*) is projected to experience slower growth due to warming, threatening its carbon sequestration capacity. Genetic diversity may enable local adaptation to these conditions (Robert et al. 2024), but loss of this adaptive capacity may have cascading effects for carbon sequestration and climate dynamics.

While some committed climate change impacts will play out over centuries to millennia, giving society the opportunity to plan and adapt, others are likely in the coming decades (Abrams et al. 2023, IPCC 2023). Similarly, committed genetic erosion represents an imminent and compounding hazard (Exposito-Alonso et al. 2022, Shaw et al. 2025). Acting early and within this lag period, can prevent irreversible losses of adaptive potential before they cascade into species extinctions, disruptions to agriculture, ecosystem collapse, and broader climate instability.

Parallel 3: We can forecast risk to guide early action

By the time genetic erosion is measurable, species are already at heightened risk of extinction, even if demographic recovery occurs (Figure 2). Once genetic variants (alleles) are lost from all populations, they are effectively irrecoverable on management timescales and long-term adaptive potential is permanently reduced (Lande and Barrowclough 1987, Allendorf et al. 2024). Preventing committed genetic erosion means identifying at-risk species *before* loss occurs, and intervening while genetic diversity can still be restored. Preventing further erosion once it has begun also remains an important and often necessary goal (Figure 1).

Detecting the warning signs of committed genetic erosion requires monitoring both genetic and demographic indicators. Ecological evidence, such as population decline, habitat fragmentation, or reduced dispersal, signals that genetic extinction debt is accumulating (O'Brien et al. 2022). Such trends are already reflected in major extinction-risk frameworks, including the IUCN Red List. However, a population's genetic diversity does not always align with Red List status (Schmidt et al. 2023, Mastretta-Yanes et al. 2024, McLaughlin et al. 2025). This mismatch may be consistent with the expected lag between population decline and detectable genetic erosion. Where genetic or genomic data exist, genetic metrics (Box 1) can reveal reduced gene flow, bottlenecks, recent inbreeding or other early signals that genetic erosion is already underway, even when overall diversity appears superficially stable (Gargiulo et al. 2025, McLaughlin et al. 2025).

Correctly interpreting genetic statistics as rates of loss, and thus measures of risk, requires clear baselines. Without this, we risk accepting current, degraded conditions as the new norm ("shifting-baseline syndrome"; Lotze and Worm 2009; Pauly 1995). Establishing consistent, globally comparable reference points is therefore critical for detecting the consequences of demographic stress early and enabling more proactive, targeted responses. Inspired by Essential Climate Variables (ECVs; GCOS 2010), biodiversity scientists developed Essential Biodiversity Variables (EBVs; Pereira et al. 2013) to quantify and report biological change worldwide. In the genetic domain, EBVs formalise key population genetic measures (Hoban et al. 2022), translating heterogeneous datasets into comparable metrics and providing a common language for monitoring across species and regions. As with ECVs, some EBVs have been translated into simplified indicators, with clear thresholds for decision-makers. Genetic diversity indicators, such as the proportion of populations within a species that are sufficiently large to maintain genetic diversity (Ne > 500), and the proportion of populations maintained (Hoban et al. 2021), provide a simple yet powerful way to track genetic extinction debt and the extent to which populations have already fallen below levels needed to sustain adaptive potential. These indicators are already being implemented in policy under the CBD (Convention on Biological Diversity 2022) and the EU Habitats Directive (O'Brien et al. 2025), although genetic diversity remains absent from major restoration frameworks (Ngeve 2025). Although thresholds in other EBVs such as heterozygosity and habitat fragmentation have been proposed and are the focus of active discussion (Andersson et al. 2022, Kurland et al. 2024), these are not yet established as critical tipping points and remain less operationalised than Ne thresholds. Further work to formalise these thresholds is urgently needed.

Forecasting future genetic change is equally vital for guiding proactive interventions. Simulations underpinned by physical climate models have been critical in climate science, projecting likely outcomes under different emissions and socio-economic scenarios (IPCC 2023). In population genetics, computational simulations serve a similar purpose: they help characterise tipping points, lags, and thresholds for genetic erosion, and forecast how demographic trends and landscape change will influence future diversity (Hoban 2014, Pinto et al. 2024). These tools also enable biodiversity managers to evaluate the consequences of various strategic options (e.g., population translocations) before losses occur, enabling them to identify when populations are likely to fall below viable thresholds, where gene flow must be maintained, and where early intervention can prevent committed genetic erosion.

Forecasting is critical in landscapes where economic development and biodiversity conservation are in direct tension, facilitating decisions on whether natural populations remain viable or are pushed toward irreversible genetic decline through disturbance. Examples include the Pilbara region of Western Australia, where mining removes cave roosts of threatened bat populations and fragments the roost network needed to maintain gene flow (Umbrello et al. 2022), and Brazil’s Atlantic Forest, where agriculture, logging, and urban expansion fragment habitats (Galán-Acedo et al. 2023). Simulations built to model such systems can help determine which areas or corridors must remain intact to avoid committed genetic erosion, and where limited development may still be compatible with maintaining connectivity (e.g., Dutcher et al. 2023; Haller and Messer 2023). In many cases, avoiding genetic decline will require leaving some land or resources unexploited, analogous to the climate concept of “unburnable carbon”, in which meeting climate targets requires leaving fossil-fuel reserves untapped (Griffin et al. 2015, Pye et al. 2020). Like these fuel reserves, land set aside for biodiversity objectives would become what climate governance terms a “stranded asset”: economically valuable on paper, but unusable in practice without committing populations to long-term genetic decline (Ploeg and Rezai 2020, Caldecott et al. 2021, Österblom and Blasiak 2021). As in climate governance, implementing these limits depends on political will and overcoming resistance from actors who stand to lose economically, while explicitly addressing trade-offs to prevent conflict and ensure equitable outcomes (Ferns and Amaeshi 2021, Meyfroidt et al. 2022, Wright and Nyberg 2024).

Parallel 4: We need proactive and ambitious action now

Just as climate and biological systems exhibit inertia, so too do political, institutional, and economic systems. Overcoming societal inertia requires systemic change in governance and finance, not just scientific clarity, as climate governance has shown. Mechanisms such as the Task Force on Climate-Related Financial Disclosures (TCFD) and the Science-Based Targets

Initiative (SBTi) evolved from voluntary commitments into widely adopted frameworks that now inform mandatory reporting and incentivise corporate leadership (Ben-Amar et al. 2024). Biodiversity reporting is beginning to follow suit through initiatives such as the Nature Positive Initiative, the Task Force on Nature-related Financial Disclosures (TNFD), and the Global Reporting Initiative's biodiversity standard, but genetic diversity remains largely absent from these frameworks (O'Brien et al. 2025). Nevertheless, promising examples exist in the private sector of companies recognising the value of assessing and maintaining genetic diversity (e.g., commercial wild salmon fisheries; Connors et al. 2022).

Challenges do, however, remain. Climate change is perceived as a global phenomenon with standardised metrics (e.g., tonnes of CO_2), whereas biodiversity loss is inherently local, context-dependent, and lacks a universally accepted measurement unit (Wauchope et al. 2024). This imbalance contributes to "carbon tunnel vision", where emissions dominate sustainability reporting while biodiversity metrics are overlooked (Jouffray et al. 2025), despite emerging quantitative thresholds for ecosystem resilience. For example, when semi-natural habitat area falls below roughly 20–25 % (at a 1 km^2 scale), critical ecosystem functions collapse. Alarmingly, about two-thirds of agricultural and urban areas globally fall below this threshold (Mohamed et al. 2024). Genetic diversity offers a complementary and quantifiable dimension of resilience, providing standardised, scalable measures that link local biological processes to global monitoring and forecasting frameworks (Mastretta-Yanes et al. 2024, Henry 2025). Embedding these metrics within global monitoring, finance, and policy systems is increasingly feasible, and supported by a growing number of tools and case studies (Hoban et al. 2021, Mastretta-Yanes et al. 2024).

Genetic diversity is declining across both threatened and non-threatened species (Mastretta-Yanes et al. 2024, Shaw et al. 2025), yet conservation policies and subsequent actions are often triggered only after a species' total population has declined to critical levels, typically in response to legal obligations or political pressure (Drechsler et al. 2011). This reflects a reactive mindset, intervening only once risk is clear, and far more difficult (or impossible) to reverse. Resilience science stresses that acting early, before thresholds are crossed, is far more effective (Folke et al. 2004). Furthermore, the costs associated with re-establishing depleted populations can be much higher than those required to maintain them above critical thresholds, despite the latter being needed over longer periods (Drechsler et al. 2011). Proactive management is therefore cost-effective and more likely to prevent irreversible loss.

The belief that emerging technologies can compensate for inaction can reinforce a reactive mindset and entrench the status quo, diverting attention from root causes and delaying meaningful change (Anderson and Peters 2016, Gifford et al. 2018). Despite decades of warnings, the world continues to rely on technological promises such as large-scale carbon capture, which the IPCC (2022) judges unlikely to deliver substantial emission reductions by 2030. If these technologies fail to perform as expected, society will be locked into a high-temperature trajectory (Anderson and Peters 2016). Biodiversity conservation faces similar risks. Advances such as CRISPR and cloning cannot recreate the evolutionary potential lost through extinction, which relies on large, diverse, self-sustaining populations. De-extinction efforts inevitably begin with extremely low genetic diversity, exposing "resurrected" populations to a re-extinction vortex (Steeves et al. 2017). While these technologies may have legitimate applications in targeted management, they remain limited. The urgent need to reduce emissions and to protect and restore genetic diversity in existing species, will rest primarily on investment in existing, proven actions.

Time lags offer a critical opportunity: the chance to intervene before losses become irreversible, and proactive management offers reason for hope (Figure 1). Because genetic diversity often declines more slowly than population size, detecting demographic problems and restoring populations before genetic erosion becomes committed, offers a window for action. For example, the Eastern North Pacific population of fin whales (*Balaenoptera physalus*) suffered a 99 % reduction in Ne during twentieth century whaling, yet retained relatively high diversity. This was likely because the bottleneck lasted about 70 years, a short period relative to the species' long generation time (~25.9 years), corresponding to three generations (Nigenda-Morales et al. 2023). A moratorium on commercial whaling was implemented within this window for action, enabling demographic recovery before genetic erosion was committed.

Species and populations face many different kinds of genetic threats, and discriminating among these helps determine the most effective management actions (O'Brien et al. 2022). A global meta-analysis suggests that several interventions can stabilise or improve genetic diversity, including supplementation (Shaw et al. 2025). Supplementation spans a continuum from facilitating natural gene flow via restored connectivity to more intensive translocations among isolated or captive populations to effect genetic rescue. Given how widespread habitat fragmentation has become, restoring gene flow is now essential in many systems (Frankham et al. 2017). Once approached with hesitancy, well-planned genetic rescue is increasingly recognised as a powerful tool for reversing inbreeding depression and restoring adaptive potential (Frankham et al. 2017, Ralls et al. 2018, Hoffmann et al. 2021). Such approaches also facilitate climate-resilient assisted gene flow, identifying and moving adaptive variation to help populations track rapidly changing environments (Meek et al. 2025). When implemented early in recovery planning and conservation management, these approaches are low-risk, relatively inexpensive, and capable of sustaining adaptive potential before genetic erosion becomes committed (Frankham et al. 2017, Ralls et al. 2018, Fitzpatrick et al. 2023, da Silva et al. 2026).

Conclusion

Conserving genetic diversity is not a niche concern; it is central to long-term ecological resilience and must become a core component of biodiversity planning. Genetic erosion is widespread, can lag behind demographic losses, and becomes committed unless proactive steps are taken to maintain and restore the evolutionary processes that sustain life on Earth. Doing so requires a shift in thinking: from reacting only after genetic erosion is detected, to also proactively safeguarding the raw material of resilience before it disappears.

Drawing from climate science, the concept of committed genetic erosion underscores the urgency of action. Just as past greenhouse gas emissions have committed the planet to future climate change impacts and potential tipping points, past and ongoing habitat loss, fragmentation, and other consequent impacts on population decline, have committed many species to future genetic erosion. The critical difference is that, unlike climate inertia, genetic inertia is tractable: erosion unfolds population by population and can be prevented if action occurs during the lag period. We cannot afford to miss this window for strategic intervention. Integrating genetic considerations into planning and policy early maximises the capacity for adaptation and recovery. To help achieve this, scientists, policymakers, practitioners, the private sector, and broader society all play a role in ensuring that genetic considerations are communicated clearly, embedded early in decisions, and underpinned by rigorous thresholds and terminology.

The solutions are well tested. In addition to monitoring, we must also apply genetic principles to management: ecological strategies that achieve genetic outcomes. Established conservation strategies, such as maintaining or improving connectivity, effecting carefully designed genetic rescue, and supporting large, viable populations, sustain the evolutionary processes that maintain genetic diversity. As such, they carry explicit genetic benefits that are too often overlooked. Recognising these genetic outcomes gives renewed urgency to implementing these strategies effectively. In much of the world, this will require applying genetic principles without direct genetic data, and prioritising large-scale actions such as habitat protection and restoration. By doing so, we intervene earlier in the extinction trajectory, acting before species are on the brink of extinction. These approaches align with major international biodiversity and development goals, supported by technical indicators that identify where losses are occurring, and which species are most at risk. Now, bold, resilience-focused biodiversity action that embeds genetic considerations into governance, finance, planning, and on-ground management is essential for maintaining adaptive potential in a rapidly changing world. The choices made today will shape the evolutionary futures of species and the ecological systems on which we depend, for generations to come.

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Conflicts of Interest

The authors declare no conflict of interest.

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Biographical narrative

The co-authors form an interdisciplinary team spanning conservation genetics, climate science, resilience research, and biodiversity policy, based at institutions across four continents encompassing government agencies, universities, botanical gardens, NGOs, and international research organisations.

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Boxes and Figures

Box 1: Signals of committed genetic erosion

Measurable changes in a population's genetic diversity are rarely the earliest warning of risk. The first indications that genetic extinction debt is accumulating are habitat loss, fragmentation and demographic decline, detectable through field monitoring or even remotely via satellite imagery (Hoban et al. 2024). These ecological signals indicate that declines in **effective population size** (**Ne**) and subsequent **genetic erosion** are likely.

Genetic diversity analyses reveal erosion already underway. Because components of genetic diversity respond to perturbation at different rates (Nei et al. 1975), comprehensive analysis can help quantify the severity, timing and trajectory of committed genetic erosion and highlight where intervention is most urgent (Frankham et al. 2010, Hoban et al. 2024).

Like species richness and diversity in ecology (Hu et al. 2006), alpha-level genetic diversity is commonly summarised using **richness** (e.g., **allelic richness**, **AR**; **Watterson's theta**, $\boldsymbol{\theta_W}$) and **evenness** (**gene diversity**, also called **expected heterozygosity**, **He**; **nucleotide diversity**, $\boldsymbol{\pi}$) metrics. Richness captures how many genetic variants (alleles) are present and is informative for long-term adaptive potential, while evenness reflects how allele frequencies are distributed and reflects short-term evolutionary responses (Caballero and García-Dorado 2013, Allendorf et al. 2024, Mergeay 2024).

While ongoing genetic monitoring is the gold standard, genetic erosion can also be detected from a single genetic snapshot. For example, following a population bottleneck, rare alleles are lost first, so richness declines rapidly. Evenness declines more slowly because it is predominantly determined by common alleles. During or shortly after demographic decline, these properties manifest as a mismatch between metrics, indicating that the population is not at mutation–drift equilibrium (Cornuet and Luikart 1996).

Reduced connectivity can generate similar mismatches: when gene flow drops below roughly one effective migrant per generation, subpopulations rapidly lose rare alleles even without detectable demographic decline (Broquet et al. 2010). This mismatch indicates a genetic extinction debt for evenness, as further loss of He or π is inevitable unless population size or connectivity increases. More generally, reduced gene flow increases genetic drift and inbreeding within each subpopulation, lowering Ne at the species level (Ryman et al. 2019). These non-equilibrium dynamics can unfold unevenly across a species' range, especially if subpopulations are permanently lost (Kurland et al. 2023).

Tests for identifying genetic erosion from a single snapshot include Bottleneck (Cornuet and Luikart 1996), Tajima's D (Tajima 1989), runs of homozygosity (ROH; Kardos et al. 2018), linkage disequilibrium (Santiago et al. 2025), or site-frequency spectrum analyses (Gutenkunst et al. 2009).

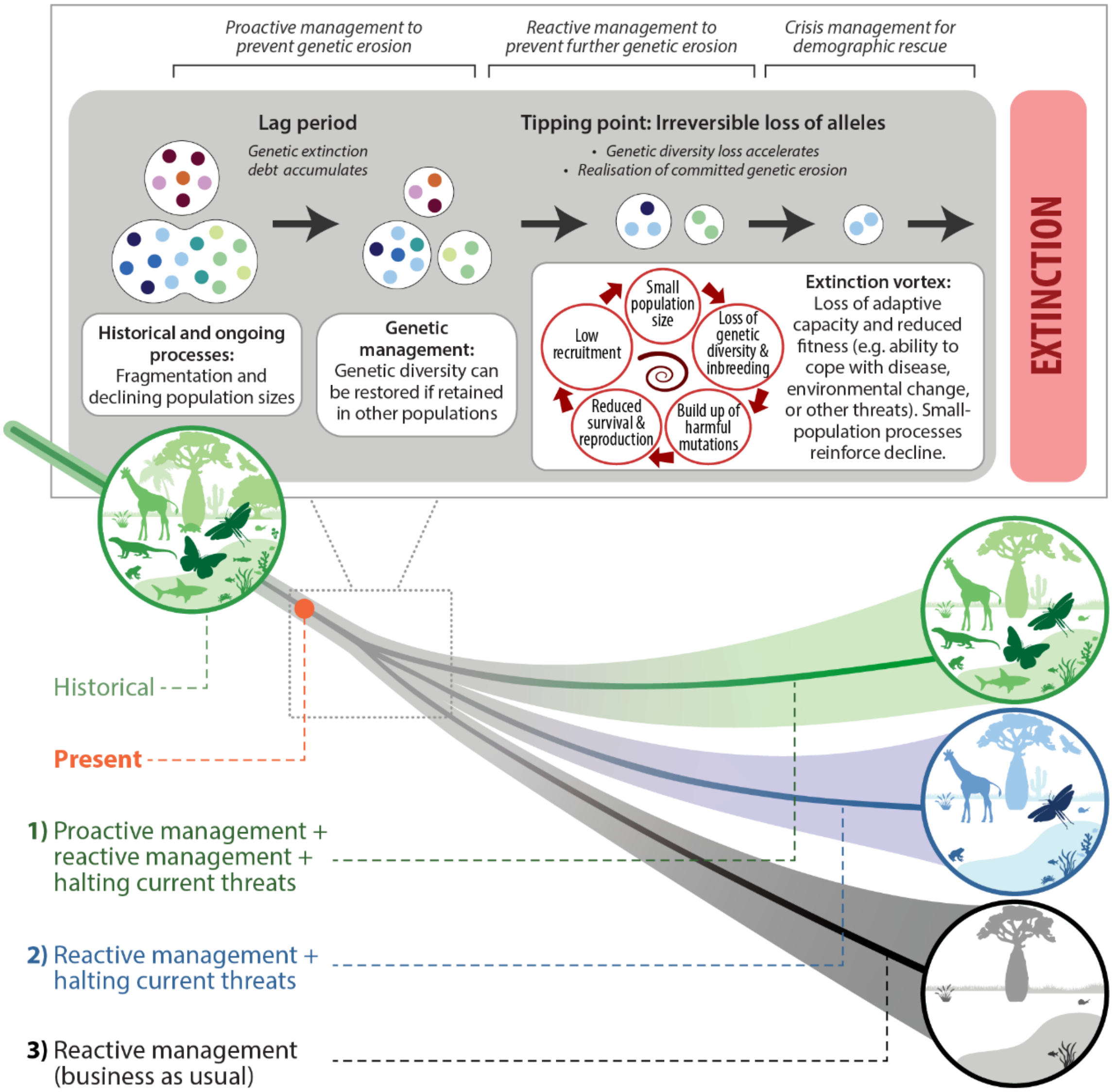
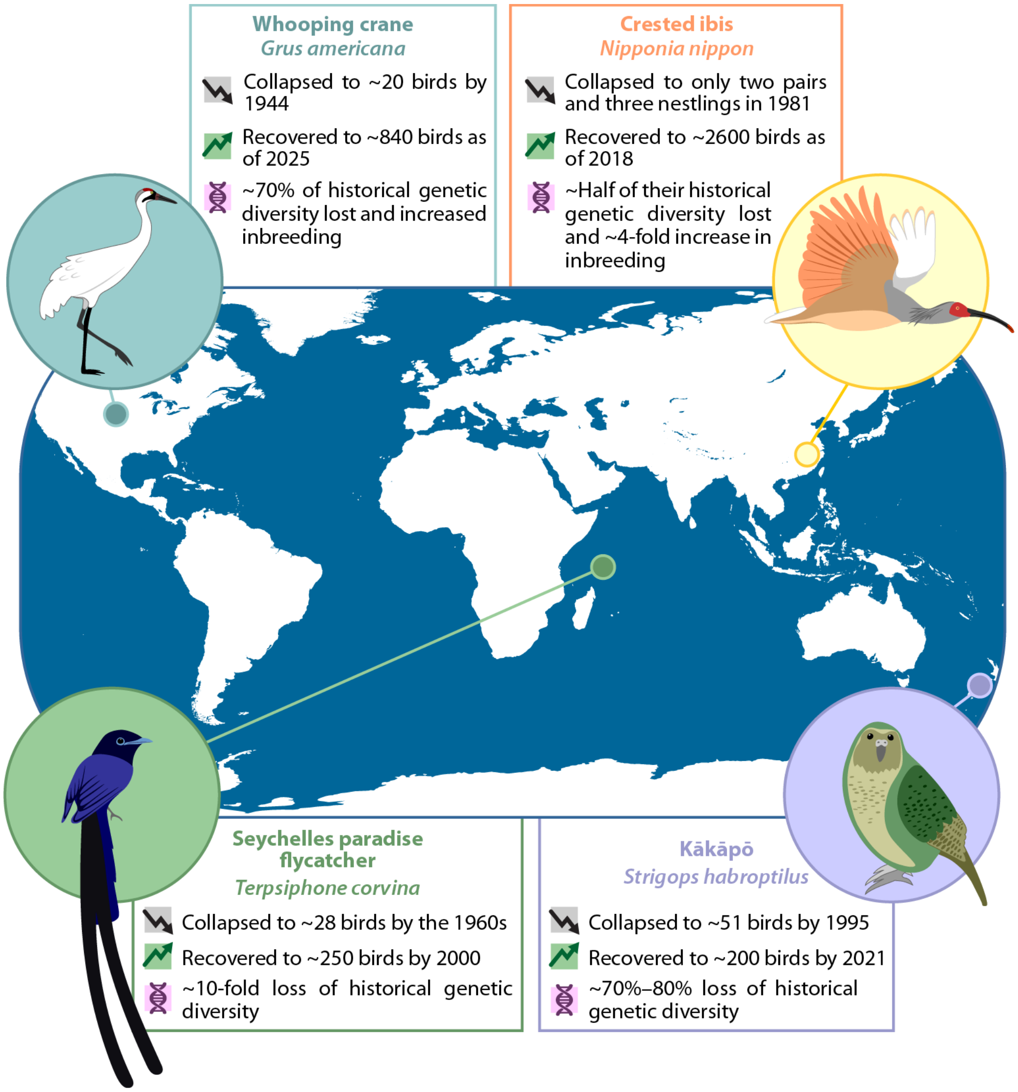


Figure 1. Conceptual diagram of biodiversity trajectories under alternative genetic management pathways. The top panel illustrates the population-level timeline occurring within the strategic window for action (grey dotted box): the period in which we can intervene before the realisation of committed genetic erosion pushes many species toward extinction. Fragmentation and population decline initiate genetic erosion, causing some immediate loss, and resulting in a lag period in which genetic extinction debt accumulates. If genetic variants persist in nearby populations, diversity at the species level can be restored through early intervention, such as by mixing populations (supplementation). After a tipping point, however, genetic erosion

accelerates and becomes irreversible, reducing adaptive capacity and fitness, and reinforcing small-population processes in a feedback loop (the “extinction vortex”). As systems move through these stages, management shifts from proactive (preventing loss) to reactive (preventing further loss) and finally to crisis management. At this stage, saving the species becomes extremely difficult and/or costly, and extinction risk is elevated due to severely depleted genetic diversity, even if demographic recovery is achieved. These often unseen genetic processes underpin three potential biodiversity futures (bottom panel: represented by species diversity on the y-axis and time on the x-axis), including: (1, green) recovery: proactive intervention to maintain adaptive capacity before genetic erosion is measurable (e.g., restoring connectivity/gene flow and sustaining large, viable population sizes), combined with threat abatement and reactive responses where needed; (2, blue) maintenance: halting current threats (e.g., no further habitat loss) alongside reactive management, reducing, but not preventing, future biodiversity loss; and (3, black) losses under business as usual, where action is delayed until genetic erosion is measurable (reactive management), resulting in biodiversity declining towards extinction, with cascading losses across ecosystems.



Whooping crane
Grus americana

- Collapsed to ~20 birds by 1944
- Recovered to ~840 birds as of 2025
- ~70% of historical genetic diversity lost and increased inbreeding

Crested ibis
Nipponia nippon

- Collapsed to only two pairs and three nestlings in 1981
- Recovered to ~2600 birds as of 2018
- ~Half of their historical genetic diversity lost and ~4-fold increase in inbreeding

Seychelles paradise flycatcher
Terpsiphone corvina

- Collapsed to ~28 birds by the 1960s
- Recovered to ~250 birds by 2000
- ~10-fold loss of historical genetic diversity

Kākāpō
Strigops habroptilus

- Collapsed to ~51 birds by 1995
- Recovered to ~200 birds by 2021
- ~70%–80% loss of historical genetic diversity

Figure 2. Global examples of realised committed genetic erosion in bird species - in all four cases substantial genetic erosion has occurred despite demographic recovery. Historical baselines derived from 19th-century specimens reveal that four well-studied bird species (the whooping crane, crested ibis, Seychelles paradise flycatcher and kākāpō) have each lost substantial proportions of their historical genetic diversity following severe population declines. Conservation actions such as translocations, captive breeding, predator control and habitat protection were essential for securing or maintaining demographic recovery and, in several cases, preventing extinction of the species. However, these efforts occurred after committed genetic

erosion had been realised. The irreversible loss of genetic diversity means that these species now persist with reduced adaptive capacity and elevated long-term extinction risk. Demographic recovery is a genuine conservation success, but genetic erosion persists even after numbers rebound. *Data sources:* whooping crane: Fontsere et al. 2025; crested ibis: Feng et al. 2019; Seychelles paradise flycatcher: Femerling et al. 2023; kākāpō: Bergner et al. 2016; Dussex et al. 2021.