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PRACTICE AND POLICY

Indicators to monitor the status of the tree of life

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Article impact statement: Phylogenetic diversity and the EDGE index make it practical and straightforward to incorporate the tree of life into biodiversity policy.

Abstract

Following the failure to fully achieve any of the 20 Aichi biodiversity targets, the future of biodiversity rests in the balance. The Convention on Biological Diversity's Kunming–Montreal Global Biodiversity Framework (GBF) presents the opportunity to preserve nature's contributions to people (NCPs) for current and future generations by conserving biodiversity and averting extinctions. There is a need to safeguard the tree of life—the unique and shared evolutionary history of life on Earth—to maintain the benefits it bestows into the future. Two indicators have been adopted within the GBF to monitor progress toward safeguarding the tree of life: the phylogenetic diversity (PD) indicator and the evolutionarily distinct and globally endangered (EDGE) index. We applied both to the world's mammals, birds, and cycads to show their utility at the global and national scale. The PD indicator can be used to monitor the overall conservation status of large parts of the evolutionary tree of life, a measure of biodiversity's capacity to maintain NCPs for future generations. The EDGE index is used to monitor the performance of efforts to conserve the most distinctive species. The risk to PD of birds, cycads, and mammals increased, and mammals exhibited the greatest relative increase in threatened PD over time. These trends appeared robust to the choice of extinction risk weighting. EDGE species had predominantly worsening extinction risk. A greater proportion of EDGE mammals (12%) had increased extinction risk compared with threatened mammals in general (7%).

By strengthening commitments to safeguarding the tree of life, biodiversity loss can be reduced and thus nature's capacity to provide benefits to humanity now and in the future can be preserved.

KEYWORDS
biodiversity indicator, biodiversity policy, Convention on Biological Diversity, edge species, evolutionary history, nature's contributions to people, phylogenetic diversity, tree of life

Indicadores para monitorear el estado del árbol de la vida

Resumen: El futuro de la biodiversidad peligra tras no haberse logrado ninguno de los 20 Objetivos de Aichi. El Marco Global de Biodiversidad (GBF) de Kunming-Montreal del Convenio sobre la Diversidad Biológica (CDB) representa la oportunidad de preservar las contribuciones de la naturaleza a las personas (PNC) para las generaciones actuales y futuras mediante la conservación de la biodiversidad y la prevención de las extinciones. Es necesario salvaguardar el árbol de la vida -la historia evolutiva única y compartida de la vida en la Tierra- para mantener en el futuro los beneficios que aporta. En el GBF se han adoptado dos indicadores para supervisar los avances hacia el cuidado del árbol de la vida: el indicador de diversidad filogenética y el índice de especies evolutivamente distintas y globalmente amenazadas (EDGE). Aplicamos ambos a los mamíferos, las aves y las cícadas del mundo para demostrar su utilidad a escala mundial y nacional. El indicador de diversidad filogenética puede utilizarse para supervisar el estado de conservación general de grandes partes del árbol evolutivo de la vida, una medida de la capacidad de la biodiversidad para mantener los PNC para las generaciones futuras. El índice EDGE se utiliza para supervisar el rendimiento de los esfuerzos por conservar las especies más distintivas. El riesgo para la diversidad filogenética de aves, cícadas y mamíferos aumentó, y los mamíferos mostraron el mayor aumento relativo de la diversidad filogenética amenazada a lo largo del tiempo. Estas tendencias parecieron sólidas a la hora de elegir la valoración del riesgo de extinción. Las especies EDGE tuvieron un riesgo de extinción predominante cada vez peor. Una mayor proporción de mamíferos EDGE (12%) presentó un riesgo de extinción creciente en comparación con los mamíferos amenazados en general (7%). Si se refuerza el compromiso de salvaguardar el árbol de la vida, se puede reducir la pérdida de biodiversidad y preservar así la capacidad de la naturaleza para proporcionar beneficios a la humanidad ahora y en el futuro.

PALABRAS CLAVE
árbol de la vida, Convenio sobre la Diversidad Biológica, contribuciones de la naturaleza para las personas, diversidad filogenética, especie borde, historia evolutiva, indicador de biodiversidad, políticas de biodiversidad

BIODIVERSITY POLICY AND THE TREE OF LIFE

Existing global policy has failed to stem biodiversity declines across the board (Díaz et al., 2019), with nations failing to meet 14 of the 20 Aichi biodiversity targets set by the United Nations Convention on Biological Diversity (CBD) and partially achieving just 6 (Secretariat of the Convention on Biological Diversity, 2020a). It has been argued, therefore, that only by being highly ambitious is there any chance of improving the outlook for global biodiversity by 2050 (Díaz et al., 2020). To rise to this challenge, parties to the CBD agreed in 2022 in the Kunming–Montreal Global Biodiversity Framework (GBF) on a set of goals and targets that aim to, among other things, protect 30% of the Earth's surface by 2030; halt human-induced extinctions of threatened species; ensure sustainable use of biodiversity and equitable sharing of the benefits it bestows; and deliver intergenerational equity (Secretariat of the Convention on Biological Diversity, 2022a).

If global policy is to effectively address biodiversity loss and secure a broad range of benefits, goals and targets should prioritize the conservation of evolutionarily distinct lineages to effectively safeguard the tree of life (Díaz et al., 2020). The tree of life represents the evolutionary relationships and history of all life on Earth from the present day back in time to the origin of life (Figure 1a). The shared and unique evolutionary history of organisms across the tree of life is a critical and often overlooked facet of biodiversity and can be measured using the metric phylogenetic diversity (PD) (Faith, 1992) (Figure 1d). PD approximates the suite of evolutionary features shared by, and unique to, the species in a given set by measuring the evolutionary history along the branches that connect them on a phylogenetic tree (a diagram that represents the evolutionary relationships of a set of organisms from one part of the

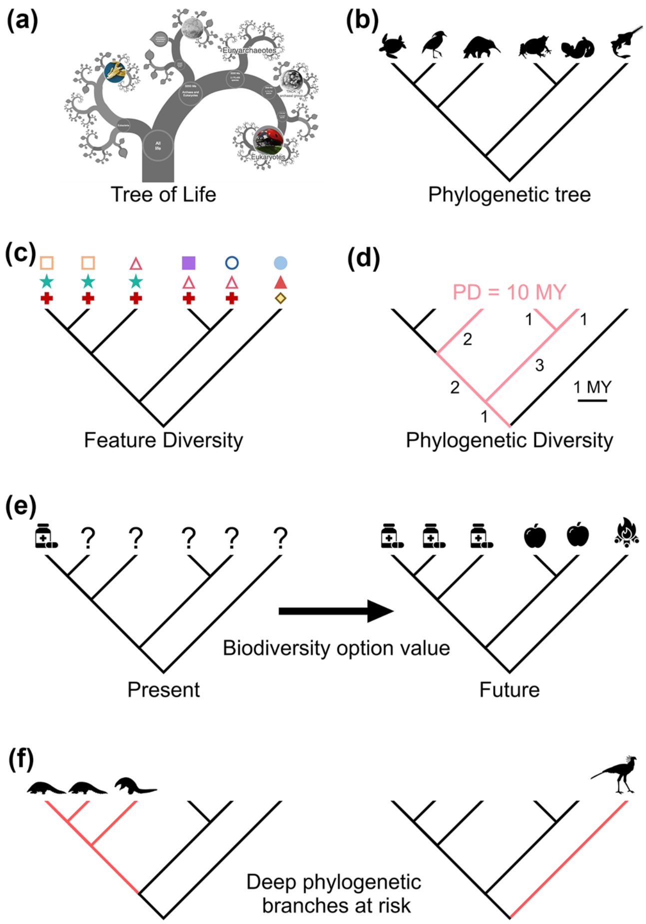

FIGURE 1 Key concepts underpinning the phylogenetic diversity indicator and evolutionarily distinct and globally endangered (EDGE) index: (a) the tree of life, which is a metaphor for the evolutionary history and relationships of all life on Earth, reaching back to the origin of life; (b) a phylogenetic tree, which represents the evolutionary relationships of a set of organisms; (c) feature diversity, which is the suite of evolutionary features (e.g., traits) retained by species today, here represented by different shapes; (d) phylogenetic diversity, which measures the amount of evolutionary history captured by a set of species (MY, millions of years); (e) biodiversity option value, the yet-to-be-discovered benefits of biodiversity; (f) deep phylogenetic branches at risk, which can be caused by either entire clades of species being threatened with extinction (e.g., pangolins) (all 8 species portrayed at left are threatened) or by threatened species isolated on long branches of the phylogenetic tree (e.g., secretarybird at right). Medicine, apple, and fire icons from Nawicon on flaticon.com. Tree of life image courtesy of onezoom.org.

tree of life) (Figure 1b). Consequently, the greater the loss of PD, and therefore of evolutionary history, the more varied and distinct features at risk of loss (Faith, 1992) (Figure 1c). As a measure of living variety, the conservation of PD is linked to the maintenance of current benefits and yet-to-be-discovered options for humanity (e.g., new medicines) provided by biodiversity, also known as the option value of biodiversity (Faith, 2016) (Figure 1e).

Empirical studies show that by focusing on PD, a larger diversity of benefits from biodiversity are protected than with random or taxonomic-based metrics (Forest et al., 2007; IPBES, 2019; Molina-Venegas, 2021; Molina-Venegas et al., 2021). For example, Forest et al. (2007) found that maximizing distribution across the tree of life when selecting sets of plant species to protect in the Cape of South Africa more efficiently retains plants with known benefits than selecting sets of plants based on generic richness alone. Similarly, Molina-Venegas et al. (2021) showed that maximizing the branches of the tree of life more efficiently safeguards a larger number and wider variety of benefits to people (hereafter benefits) including materials, food, medicine, and fuels, than a random selection. Maintaining the current benefits and option value of biodiversity is therefore a key mechanism for achieving intergenerational equity. This maintenance of options is particularly important in the context of a changing environment (IPBES, 2019; Molina-Venegas et al., 2021; Pollock et al., 2017; Robuchon et al., 2021; Veron et al., 2019) and the challenges biodiversity faces due to anthropogenic pressure (Dirzo et al., 2014; O'Bryan et al., 2020).

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) adopted an indicator that estimates the percentage of a taxonomic group's PD that is represented by threatened species (hereafter IPBES PD indicator) to monitor the status of the tree of life and thus biodiversity's capacity to provide nature's contributions to people (NCPs). The NCPs comprise the contributions from nature from which we benefit, such as food provision, clean water, and medicines (Díaz et al., 2019; IPBES, 2019). IPBES links PD to the maintenance of options (the overall capacity of biodiversity to support a good quality of life into the future; NCP 18 in the IPBES framework), and thus the continued provision of medicinal, biochemical, and genetic resources (NCP 14) and sources of learning and inspiration (NCP 15; Díaz et al., 2019; IPBES, 2019). Initial estimates of the IPBES PD indicator have been produced for several clades (amphibians, corals, cycads, birds, mammals, and squamates) as part of IPBES's regional and global assessments (Faith et al., 2018; IPBES, 2018; Martín-López et al., 2018).

An effective approach for averting the greatest losses across the tree of life is to focus on distinctive species that embody a disproportionate amount of threatened evolutionary history (Figure 1f; Díaz et al.,2020; Redding & Mooers, 2015). The extinction of highly evolutionarily distinct species, with few close relatives on the tree of life, results in the irreversible loss of not only their unique characteristics but also their potential benefits and should be avoided (Díaz et al., 2020; Isaac et al., 2007; Rounsevell et al., 2020). The IUCN has long recognized the importance of conserving distinctive species (IUCN, 1980) and resolved in 2012 to halt the loss of evolutionarily distinct species (IUCN, 2012). Evolutionarily distinct species are increasingly recognized as of particular conservation importance globally (Díaz et al., 2020; UNEP-WCMC et al., 2018), and their protection will play an important role in safeguarding future benefits derived from biodiversity (Molina-Venegas, 2021).

In recognition of the importance of conserving the tree of life, the GBF—agreed in December 2022—includes 2 indicators that explicitly monitor the status of the tree of life (Secretariat of the Convention on Biological Diversity, 2022b). The first, the expected loss of PD, has been adopted as a complementary indicator for both Goal A (halting extinction and reducing extinction risk and rates 10-fold by 2050) and Goal B (sustainable use of biodiversity to maintain and value NCPs). The second, the changing status of evolutionary distinct and globally endangered species (EDGE index), has been adopted as a component indicator for Goal A and a complementary indicator for target 4 (halt extinction and reduce extinct risk of threatened species).

We expanded details for the 2 indicators and applied them to the world's birds, mammals, and cycads (data sources and full methodologies in Appendix S1). First, we outlined the expected loss of PD indicator (hereafter GBF PD indicator), which builds on the approach used for the IPBES PD indicator to track the status of the tree of life across entire taxonomic groups. Second, we outlined the EDGE index, a species-focused indicator that tracks the change in conservation status for the most evolutionarily distinct and threatened species through time. We considered how these indicators complement and expand on existing tools for monitoring biodiversity and how they can be incorporated into existing policy frameworks, such as the CBD, at national and global scales.

PD INDICATOR

Rationale

For the GBF PD indicator, we used a methodological update to the initial methodology of the IPBES PD indicator that improves its robustness and applicability for biodiversity policy at regional and global scales. Specifically, this update incorporates standardized IUCN Red List extinction risk data for all species in taxonomic groups, where available, for multiple time points, where applicable (Henriques et al., 2020; IUCN, 2020), to generate trends in the status of PD based on the established expected PD loss framework (Faith, 2008; Faith et al., 2018). Expected loss is an established probabilistic approach to measuring the status of diversity (Weitzman, 1998; Witting & Loeschcke, 1995). The expected loss of PD is the amount of evolutionary history expected to be lost in a given amount of time based on the current extinction risks faced by the set of species (Faith, 2008). This is now widely applied to inform biodiversity monitoring (Faith et al., 2018; Gumbs et al., 2020; IPBES, 2019) and conservation action (Forest et al., 2018; Isaac et al., 2007; Nunes et al., 2015; Redding & Mooers, 2006; Steel et al., 2007).

When an ancestral branch of the tree of life has several descendant species that are all at low risk of extinction, the risk of losing that branch is relatively low because it would require all descendants to become extinct. However, as the probability of extinction increases for each descendant species, the associated risk of losing the ancestral branch that they share also increases. This interaction between related species' risk of extinction is known as "PD complementarity" (Faith et al., 2004). The greater the proportion of long branches of the tree of life that have only threatened species as descendants, the greater the expected loss of PD. For example, the branch that connects pangolins to all other mammals is long and continues to exist only while at least 1 of the 8 descendent species of pangolin survive (Figure 1f). At present, all 8 are threatened, together representing an entire mammalian order at risk of extinction. Alternatively, the loss of threatened species with no close living relatives—such as the secretarybird (*Sagittarius serpentarius*), the only extant member of its entire family—will also lead to the loss of deep branches of the tree of life (Figure 1f).

The inclusion of PD complementarity is widely recommended for accurate calculation of expected PD loss (Faith, 2008; Faith et al., 2018; Gumbs et al., 2023; Nunes et al., 2015; Steel et al., 2007) but was not used for the formulation of the IPBES PD indicator. Instead, the IPBES PD indicator summed the evolutionary distinctiveness (ED) scores (i.e., where the PD of each phylogenetic branch is shared equally among all species that descend from it). For example, for a branch with 2 descendants, both species would receive 50% of the branch's PD (Isaac et al., 2007) assigned to threatened species (Faith et al., 2018). The proportion of total ED of the clade contributed by threatened species was then used as the indicator value. This approach may overestimate the amount of threatened PD by ignoring PD complementarity because the ED score of a threatened species includes the contributions of deeper branches of the tree of life, irrespective of whether they are also shared with nonthreatened species and thus are unlikely to be lost (see "Comparison with IPBES Methodology" [Appendix S1]).

Our updated approach to estimate the GBF PD indicator explicitly incorporates the concept of PD complementarity to directly estimate the expected loss of branches of the tree of life. We used probabilities of extinction—converted from IUCN Red List categories (Gumbs et al., 2023; Mooers et al., 2008)—to calculate the amount of PD expected to be lost from each branch of the tree of life, based on the probability that the set of species responsible for the survival of that branch are lost in the future. We assigned increasing values of extinction risk to IUCN Red List categories of increasing severity, rather than treating all threatened species at equal risk of extinction (as in the IPBES ED approximation of Faith et al. [2018]) (Appendix S1). Thus, our GBF PD indicator is better aligned with the use of extinction risk data in the IUCN Red List Index (RLI), another key biodiversity indicator that tracks the trends in overall extinction risk for entire taxonomic groups (Butchart et al., 2004).

We used an extinction risk quantification in which probability of extinction halves with every decrease in red-list category, from 0.97 for critically endangered to 0.485 for endangered and so forth, following Gumbs et al. (2023) (detailed methods in "PD Indicator" in Appendix S1). This calculation aligns with the extinction risk values used to calculate EDGE scores for identifying priority species (see "EDGE index" below) and provides the most conservative estimates of relative change for each group (see "PD Indicator Sensitivity Analyses" in Appendix S1).

Real-world application

We examined the utility of our updated methodology for the GBF PD indicator by generating it for 3 taxonomic groups: birds, mammals, and cycads (detailed methods and data sources

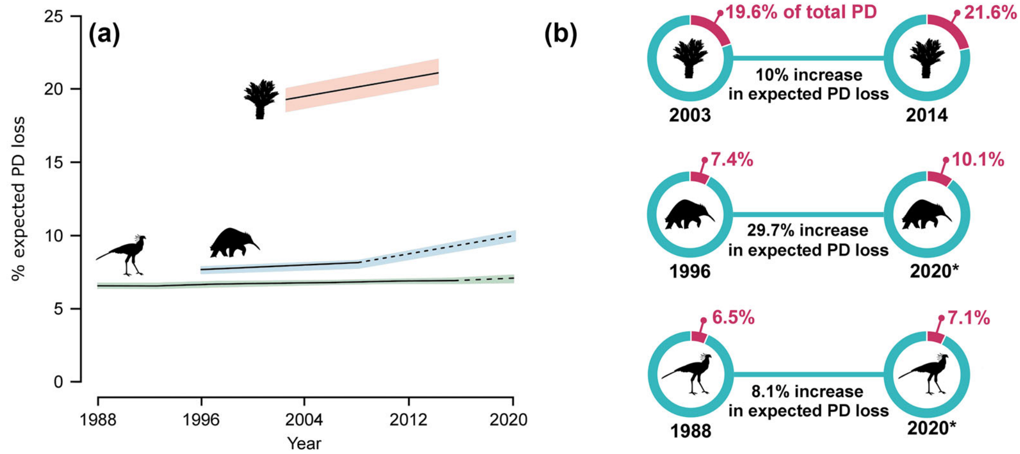

FIGURE 2 Loss of phylogenetic diversity (PD) over time: (a) trends in percentage of expected PD loss (i.e., percentage of total evolutionary history of the clade expected to be lost due to extinction of species) for the world's mammals (blue), birds (green), and cycads (pink) based on current and historical International Union for the Conservation of Nature (IUCN) Red List assessments and (b) details of trends (circles, total PD of the clade; red, percent expected loss for the baseline [left circle] and latest [right circle] time points; percentages under the connecting line, percent change in expected PD loss between each time point; 2020 time points, not official IUCN Red List Index [RLI] time points, latest status of these assessments for both clades [Appendix S1]; dashed trend lines, official RLI data for 2020 time points; shading, range of values). There are insufficient repeated IUCN Red List assessments to produce a 2020 time point for cycads.

in Appendix S1). We calculated the percentage of total PD for each clade expected to be lost across a distribution of 100 phylogenetic trees to capture phylogenetic uncertainty at each time point for which comprehensive IUCN Red List assessment data were available (Figure 2; Appendix S1). Given increased levels of extinction risk through time for each of the 3 taxonomic groups, trends in their expected PD loss are worsening (Figure 1). Mammals had the greatest projected relative increase in expected PD loss (median 29.7% increase from 1996 to 2020). Due to their elevated extinction risk, cycads (21.6%) were predicted to lose more than double the proportion of PD than mammals (10.1%), and 3 times that of birds (7.1%) (Figure 2).

We also calculated the GBF indicator across the 100 trees for each taxonomic group with 2 alternative conversions of IUCN Red List categories to extinction probabilities to examine the influence of extinction risk quantification on the resulting values (see "PD Indicator Sensitivity Analyses" in Appendix S1). Although the magnitude of expected PD loss varied depending on the method of conversion of red-list categories to probabilities of extinction, the trends in relative change through time were consistent (within 10% among all groups) (expanded results in Appendix S1). In comparison, the IPBES PD indicator estimated levels of expected PD loss to be at least 2 times higher than those from the most pessimistic probabilities of extinction (Appendix S1). This is to be expected given the IPBES PD indicator methodology did not incorporate PD complementarity, which we included to more accurately estimate the expected loss associated with branches with multiple descendants.

Outlook

The GBF PD indicator provides a useful tool to indicate the capacity of biodiversity to provide future options to support a good quality of life (Díaz et al., 2019; Faith et al., 2018). As we demonstrated, although currently listed as complementary, the GBF PD indicator can serve as a headline indicator (the only indicator type for which reporting is compulsory) for Goal B of the GBF. Goal B currently has a single headline indicator, "services provided by ecosystems" (Secretariat of the Convention on Biological Diversity, 2022b), which lacks an agreed upon methodology, required before 2025. We argue that the adoption of the PD indicator as a headline indicator for Goal B of the GBF would represent a unique opportunity to incorporate an indicator that is directly linked to the expected loss of the nonmonetary benefits and future options that biodiversity provides, which must be secured (Secretariat of the Convention on Biological Diversity, 2022a). Further, given the link between PD and the provision of benefits, the PD indicator is well suited as an indicator for target 9 of the GBF, which aims for the sustainable use of biodiversity to ensure the provision of benefits for people. As national, regional, and global policies to address biodiversity loss and the resulting impacts on nature's capacity to provide benefits for future generations emerge or are revisited, the GBF PD indicator can provide an established and available tool to monitor the status of the tree of life.

EDGE INDEX

Rationale

The EDGE approach is an established tool for identifying evolutionarily distinct species whose conservation should be prioritized to avoid particularly large losses of PD (Gumbs et al., 2023; Isaac et al., 2007). EDGE species are threatened species for which there is 95% confidence that their EDGE scores are above the median for their taxonomic group. The EDGE score of a species can be calculated from expected PD loss trees (i.e., phylogenetic trees on which the branch lengths have been multiplied by the overall probability of extinction of all descendant species to calculate the expected PD loss associated with each phylogenetic branch). For each species in an expected PD loss tree, the lengths of all phylogenetic branches connecting a species at the tip to the root of the tree are summed to provide the EDGE score (Gumbs et al., 2023). Such expected PD loss trees are generated to calculate the GBF PD indicator, outlined above, which sums the branch lengths of such a tree to determine the overall expected PD loss of a clade (Appendix S1). Thus, the data used to generate the GBF PD indicator can, in turn, be used to calculate the EDGE index.

The EDGE index uses available extinction risk data for the world's most evolutionarily distinct and threatened species to provide explicit monitoring of documented extinctions and increases and decreases of extinction risk category on the IUCN Red List through time for these irreplaceable sets of species. To generate the EDGE index, we calculated 3 components for a given point in time (expanded methods in "EDGE Index" in Appendix S1): changes in the number of EDGE species, trending upward as more highly evolutionarily distinct species become threatened or trending downward as highly distinctive species move from threatened to nonthreatened categories; number of EDGE species from a previous time point that have since been declared critically endangered (possibly extinct), extinct in the wild, or extinct; and changes in extinction risk of EDGE species from a previous time point. For the latter component, those moving into more severe categories (uplistings) indicated increased extinction risk of the most distinctive and threatened species, whereas increased numbers of EDGE species moving into less severe categories (downlistings) indicated decreased extinction risk among these species.

Real-world application

We used the expected PD loss data generated to calculate the GBF PD indicator for birds, mammals, and cycads to create the EDGE index for each group at the same time points used for the GBF PD indicator (Figure 3). For each time point, we used the median EDGE score for each species, taken from the distribution of 100 phylogenetic trees generated for the GBF PD indicator at that time point (Appendix S1). Priority EDGE species for a given time point were identified as threatened species with above median EDGE scores across 95% of phylogenetic trees (Gumbs et al., 2023; Isaac et al., 2007). The whole process was repeated, and each of the 4 components of the EDGE index were calculated for each time point.

We found that the number of EDGE species increased for all 3 taxonomic groups between their first and most recent comprehensive IUCN Red List assessments (Figure 3a,c,e). Further, the conservation status of EDGE species deteriorated, with greater numbers of uplistings than downlistings for each group, most notably for EDGE mammals, for which 66 EDGE species (12%) increased in extinction risk from 1996 to 2008 (Figure 3b,d,f), compared with just 7% of all threatened mammals. Each group had at least 1 species transition to an extinct category, including the Baiji (*Lipotes vexillifer*), the only species in its entire family (Lipotidae), and Spix's macaw (*Cyanopsitta spixii*), the only species in its genus.

Finally, we investigated the ability of various metrics of ED to capture overall PD and threatened PD, given the ever-growing number of metrics to choose from (Díaz et al., 2020; Faith et al., 2004; Gumbs et al., 2023; Isaac et al., 2007; Redding & Mooers, 2006; Steel et al., 2007). We found that the distinctiveness measure employed for the EDGE index captured significantly more overall PD and threatened PD than other metrics when looking at the world's mammals (see "EDGE Index Sensitivity Analyses" in Appendix S1).

Outlook

The EDGE index is designed to complement, rather than supplant, existing broader species measures, such as the RLI and Living Planet Index, to ensure evolutionarily distinct species are prioritized as part of any effort to reduce extinction rate and risk (Díaz et al., 2020; Secretariat of the Convention on Biological Diversity, 2020b, 2021). The inclusion of the EDGE index in the GBF as a component indicator for Goal A (and complementary indicator for target 4) is a significant acknowledgment that the conservation of evolutionary history must be prioritized to achieve the goals of biodiversity policy. Given the established history of the EDGE approach and its relevance for species conservation, the EDGE index has the potential to be widely applicable at the national and global scale to inform any policies and priority setting focused on averting extinctions.

CONSERVING THE TREE OF LIFE POST-2020

Equality of extinctions

Conservation discourses have traditionally focused on ecosystems, species, and populations—overlooking PD—but this risks isolating the conservation of biodiversity from recognition of the benefits and option values that it provides by simply assuming these values will be maintained under current conservation paradigms. For example, without considering PD, it is possible to select sets of threatened species for conservation that would actually fail to avert the greatest losses across the tree of life (low EDGE strategy in Figure 4; also see "Not All Extinctions Are Equal" in Appendix S1). Conversely, conserving the same number of evolutionarily distinctive species ("high EDGE" strategy; Figure 4) would avert large amounts of imperiled PD, particularly when focusing on the most acutely threatened species (CR–EN extinction scenario in Figure 4).

Strengthening policy commitments to the tree of life

PD can evidently provide a useful tool for the monitoring of biodiversity and its associated values for a myriad of global,

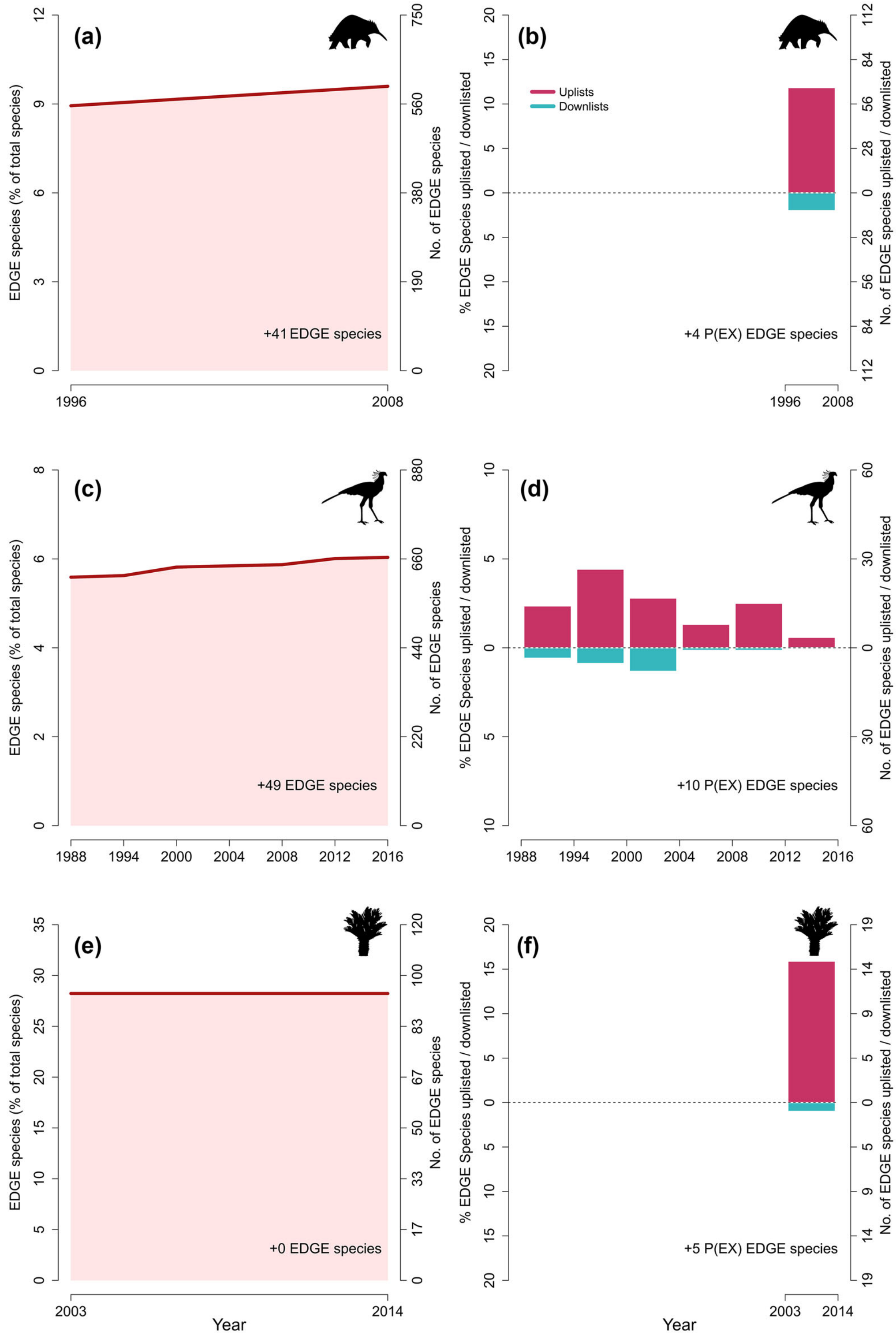

FIGURE 3 The evolutionarily distinct and globally endangered (EDGE) index for monitoring trends in extinction risk for priority EDGE species: (a, c, e) changes through time in the total number of EDGE species per clade and (b, d, f) changes in extinction risk (uplistings and downlistings [species moving into more or less threatened red-list categories, respectively]) and number of species that went extinct (P[EX]) (Appendix S1) within sets of EDGE species for (a, b) mammals, (c, d) birds, and (e, f) cycads. Changes in total number of EDGE species and extinct species are cumulative from baseline time point (dotted line). Number of uplistings and downlistings is for each period between time points.

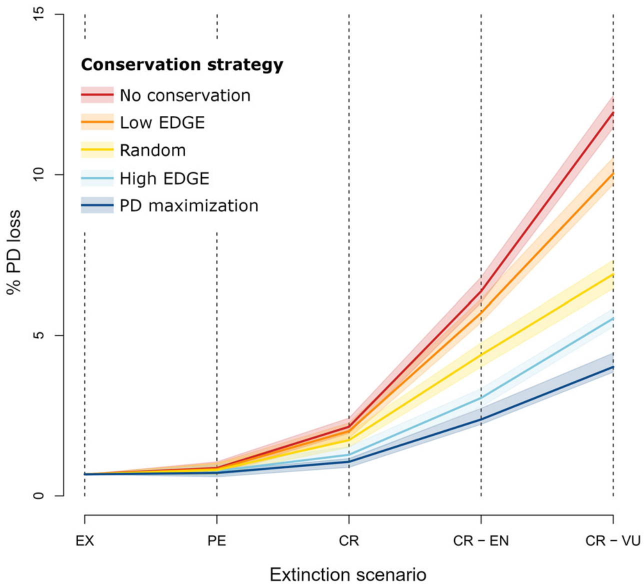

FIGURE 4 Variation in magnitude of expected loss of phylogenetic diversity (PD) under different conservation strategies selecting subsets of species across 4 extinction scenarios for the world's mammals (PE, possibly extinct [31 spp.] and extinct [84 spp.] species on the International Union for the Conservation of Nature Red List; CR, critically endangered [197 spp.] also lost; CR+EN, all endangered species [504 spp.] also lost; CR+EN+VU, all vulnerable species [543 spp.] are lost; colored lines, median values of PD lost under each of the 5 conservation strategies across each extinction scenario; no conservation, no species conserved under each extinction scenario; low EDGE, species in lowest quartile of expected PD loss contributions conserved [low-ranking EDGE species] as a non-PD-informed conservation model; random, random set of species from those that meet the extinction scenario criteria, equal in size to 1 quartile, conserved as null model; high EDGE, species in uppermost quartile of expected PD loss contributions conserved [high-ranking EDGE species] as a PD-informed conservation model; PD maximization, ideal selection of species maximizes PD conserved based on a greedy algorithm). Phylogenetic diversity loss calculated across 100 mammalian trees (details in Appendix S1). EDGE, evolutionarily distinct and globally endangered.

regional, and national policy frameworks. IPBES's embrace of PD and option value and the initial reporting of their PD indicator at global and disaggregated regional levels (IPBES, 2018) provided a solid foundation for the wider adoption of PD into biodiversity policy. Given IPBES's role in harnessing scientific expertise to disseminate policy-relevant knowledge and catalyze the adoption of knowledge-based policies, it is important that the body continues to report on and advocate for the conservation of the tree of life. Future reporting of the status of PD at global and regional levels in IPBES assessments should therefore adopt the methodology outlined here, for consistent and more robust reporting across policy platforms, and incorporate other taxonomic groups as data become available.

The inclusion of both the PD indicator and EDGE index in the Kunming–Montreal GBF represents a significant advance toward placing evolutionary history at the core of biodiversity policies. However, there is still room for improvement. Although intergenerational equity is a central ambition in the GBF, there is currently a real risk that no headline indicator will be included that links the maintenance of biodiversity to the provision of benefits for future generations in a changing world. The adoption of 1 or both of the indicators outlined here as headline indicators for the GBF would signify a definite commitment to averting the greatest losses across the tree of life to safeguard the option value of biodiversity.

National disaggregation

Given the need for nations to determine targets relevant to their own circumstances and local values and to monitor their individual progress toward national and global targets (Rounsevell et al., 2020), it is essential that biodiversity indicators can be disaggregated to regional and national levels. In fact, the capability to monitor the status of global values of biodiversity, such as option value, at a national level is particularly important given that current local-scale conservation efforts can often neglect these species (Owen et al., 2019). Indeed, the benefits to humanity bestowed by species of medicinal importance, for example, or those species that inspire awe for the natural world transcend political borders and generations. Thus, although national responsibility for the preservation of biodiversity is particularly vital given the high numbers of species that are endemic to individual countries (Pitman & Jørgensen, 2002), it must also be recognized that biodiversity loss in 1 nation is often driven by consumption patterns elsewhere. It is therefore important for nations driving biodiversity loss beyond their national borders to also commit to direct conservation efforts to avert losses to which they contribute.

Both the indicators proposed here can be effectively disaggregated to national levels (Figure 5). To illustrate the simplicity of this, we generated the expected PD loss indicator and EDGE index (all components) for the birds of Kenya (Figure 6) (detailed methods in "National Disaggregation" in Appendix S1), just 1 example of a biodiverse country. We calculated the national-level output of the PD indicator with the tree of life for the birds of Kenya, considering only the persistence of the set of species in Kenya as relevant to maintaining Kenya's branches of the tree and thus quantifying their national contributions to people. Because the EDGE prioritization approach must be calculated from the global set of species to retain comparability (Gumbs et al., 2018; Isaac et al., 2007), the national-level output of the EDGE index draws the set of EDGE species for Kenya from this global pool of priority species before recalculating all components of the EDGE index (Figure 5; Appendix S1). Both indicators retained global relevance when calculated at a national level due to the global values associated with the branches of the tree of life held by the species occurring in respective territories.

Taxonomic scope and indicator reporting

It is important for any indicator to be easily calculable or readily available for use by all stakeholders. The data necessary to estimate the evolutionary relationships and extinction risk of sets of species are increasingly available for large parts of the tree of life (Cox et al., 2022; Hinchliff et al., 2015; Nic Lughadha

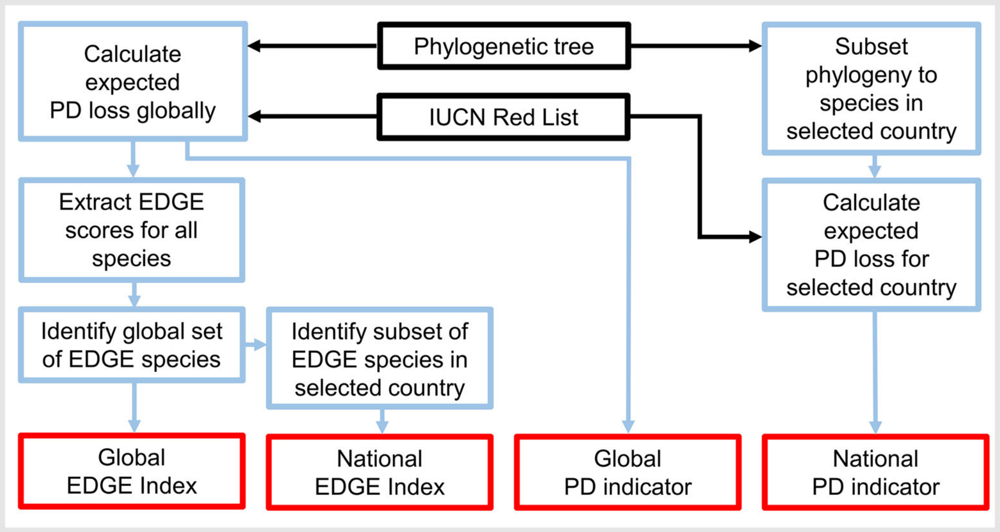

FIGURE 5 The process to generate global- and national-level phylogenetic diversity (PD)-based indicators adopted by the UN Convention on Biological Diversity's post-2020 monitoring framework (black, data sources; blue, processing stages; red, metrics).

et al., 2020). With the IPBES PD indicator, data made available as part of the commitment by the Zoological Society of London's EDGE of Existence program (Gumbs et al.,2023 were used. This program has been the central repository for ED and EDGE data for more than a decade and provides regularly updated ED scores for taxonomic groups for which data are available (Gumbs et al., 2018; IPBES, 2019). The Royal Botanic Gardens, Kew (RBG Kew) and partners have also committed to produce EDGE scores for the world's seed plants (Forest et al., 2018; Royal Botanic Gardens, Kew, 2021). As the EDGE of Existence program and RBG Kew transition to generating EDGE species priorities based on principles applied here, the data underpinning the GBF PD indicator and EDGE index will be maintained and regularly updated for all animal and plant groups for which such calculations are possible.

Despite continued advances in the ability to map extinction risk across the tree of life (Jin & Qian, 2019; ter Steege et al., 2015), more resources are needed to ensure any global biodiversity indicators are applicable to more than a narrow set of well-studied species groups and are regularly compiled to enable effective monitoring of the current state of biodiversity. Given advances in our understanding of the tree of life and extinction risk for animals (Andermann et al., 2020; Colston et al., 2020; Hinchliff et al., 2015; Wong & Rosindell, 2022) and plants (Borsch et al., 2020; Jin & Qian, 2019; Nic Lughadha et al., 2020; ter Steege et al., 2015; Yessoufou et al., 2017), the taxonomic scope of both indicators presented here is set to increase between now and 2030.

Baselines for the 2 indicators are also in the process of being generated for amphibians, reptiles, ray-finned fish, sharks and rays, crayfish, and various plant groups. As it becomes increasingly possible to predict extinction risk for large numbers of species (Zizka et al., 2022), the taxonomic coverage of the 2 indicators will remain at a minimum comparable to that of other related biodiversity indicators, such as the IUCN RLI. To aid the dissemination of these data and ease reporting of the proposed indicators, the IUCN Species Survival Commission's Phylogenetic Diversity Task Force has committed to generate both indicators at global and national levels and make these publicly available and accessible through an online tool currently in development. However, further research into the influence of baseline selection and disaggregation methods on the resulting indicators will be valuable to optimize their utility into the future.

CONCLUSIONS

We highlighted the PD indicator and EDGE index, both of which make it practical and straightforward to incorporate the tree of life—and the benefits it provides—into biodiversity policy at global, regional, and national scales. The indicators build on existing and widely accepted approaches to measuring biodiversity and extinction risk to generate monitoring tools that complement existing species-based indicators and conservation measures. The GBF PD indicator has the capacity to link the preservation of biodiversity to the maintenance of benefits, bolstering intergenerational equity. The EDGE index and its components are based on the well-established EDGE approach to monitoring the conservation status of the world's most evolutionarily distinct species.

To be truly ambitious, global biodiversity policy must aim to safeguard the tree of life (Díaz et al., 2020). The inclusion of indicators for the tree of life in the Kunming–Montreal GBF is a timely recognition of the importance of conserving evolutionary history, although commitments in the GBF, and in biodiversity policy more widely, need to be strengthened. Without this, great losses of evolutionary history are likely, including the loss of their associated options and benefits for current and future generations. But if evolutionary history can be preserved,

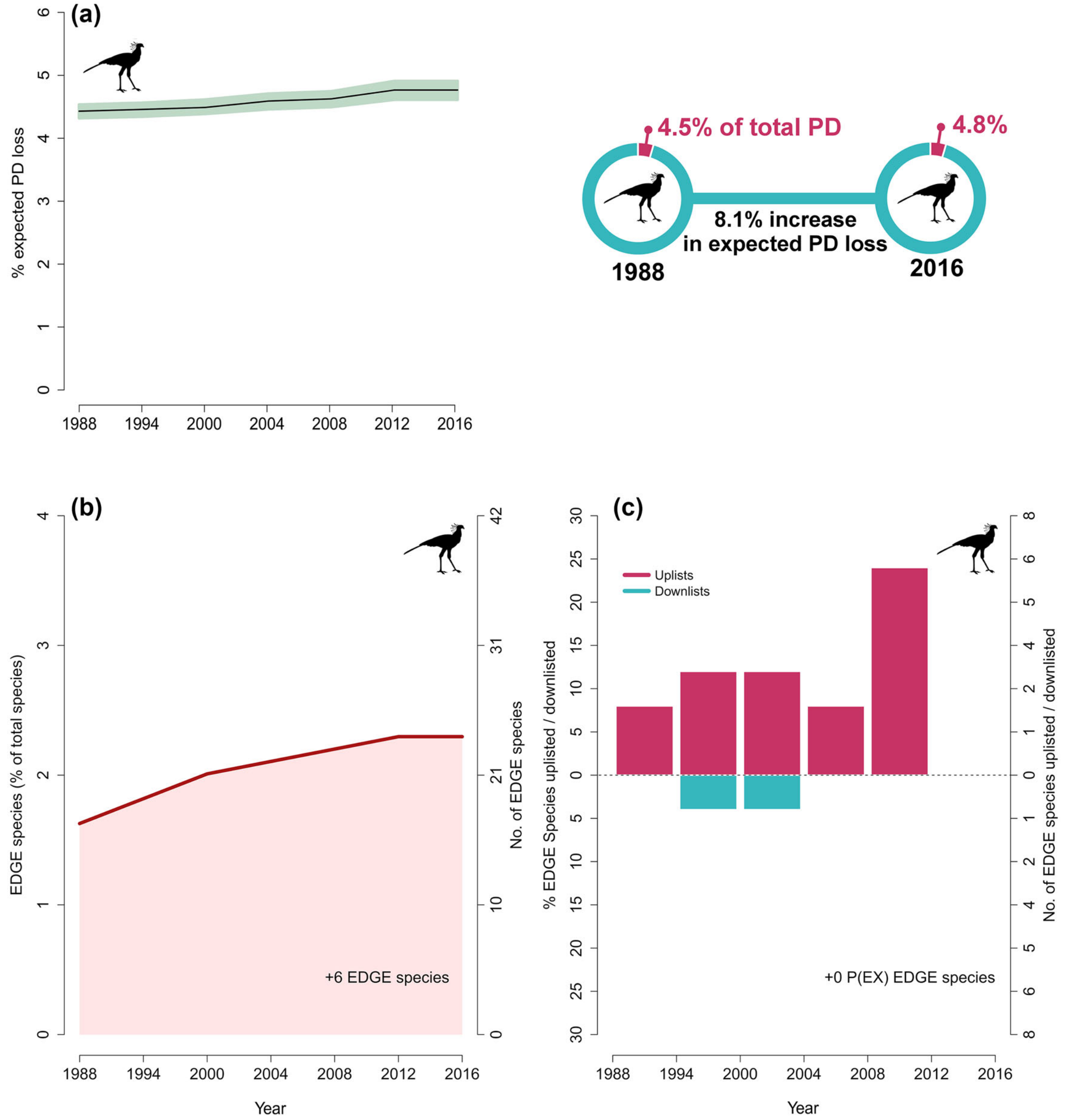

FIGURE 6 Example of national disaggregations for (a) phylogenetic diversity (PD) indicator calculated as the percentage of the total PD associated with bird species present in Kenya expected to be lost from Kenya should those species become extinct and (b, c) evolutionarily distinct and globally endangered (EDGE) index for birds of Kenya (subset from the global pool of priority EDGE bird species to ensure national priority species align with those of global value). See Appendix S1 for detailed methods underpinning these national disaggregation approaches.

much of the global value of nature's contributions to humanity now and into the future can be saved.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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