Extinct in the Wild: The precarious state of Earth's most threatened group of species

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Teaser: The perilous state of Extinct in the Wild species demands urgent attention and action.

Abstract: Extinct in the Wild (EW) species are placed at the highest risk of extinction under the International Union for Conservation of Nature Red List, but the extent and variation in this risk has never been evaluated. Harnessing global databases of *ex situ* animal and plant holdings, we report on the perilous state of EW species. Most EW animal species, already compromised by their small number of founders, are maintained at population sizes far below the thresholds necessary to ensure demographic security. Most EW plant species depend on live propagation by a small number of botanic gardens, with a minority secured at seed bank institutions. Both extinctions and recoveries are possible fates for EW species. We urgently call for international effort to enable the latter.

EXTINCT IN THE WILD: AN OVERLOOKED CATEGORY OF SPECIES AT RISK

A crisis of species loss unprecedented in human history continues to deepen (*1*, *2*). Over the last century, extinctions in well-understood groups such as vertebrates have far exceeded what would be considered to be a normal background rate based on the fossil record (*3*). The wave of extinctions lies largely ahead: the proportion of species threatened with extinction amongst the most comprehensively assessed speciose groups ranges from 13% in birds to 42% in gymnosperms (*4*), and patterns of decline and extinction in poorly known taxa may be even more severe (*5*, *6*). However—despite the failure to meet similar commitments in the 2010 Aichi Biodiversity Targets (*7*)—the 2022 Kunming-Montreal Global biodiversity targets to halt extinctions and recover species (*8*) should be regarded as achievable. This is because the field of conservation biology is continuing to demonstrate that the status of threatened species can be improved, and extinctions in the wild prevented and even reversed. The conservation status of the world's vertebrates, though deteriorating, would be significantly worse were it not for conservation interventions (*9*). Indeed, 28-48 extant bird and mammal species would have gone extinct between 1993 and 2020 were it not for actions such as habitat protection, translocation, and *ex situ* conservation using breeding facilities and zoos (*10*). *Ex situ* conservation using botanic gardens and seed banks has also been used to support the restoration of at least eight plant species and populations that had disappeared from their indigenous range (*11*). Amongst these endeavours sits a category of species representing a striking nexus of responsibility, vulnerability, and opportunity: those that—having been entirely extirpated in the wild—exist solely in zoos, aquariums, botanical gardens, or seed banks, i.e., those that qualify for the International Union for Conservation of Nature Red List of Threatened Species (Red List) category of Extinct in the Wild (EW) (*4*). This category is applied to any species "known only to survive in cultivation, in captivity or as a naturalized population (or populations) well outside the past range" (*12*).

Species that have found themselves restricted to *ex situ* care arrived there through a variety of means. In some cases, individuals were collected from highly threatened populations with the specific aim of species conservation. The lizard fauna native to Christmas Island in the Indian Ocean, for example, suffered significant declines starting in the 1970s due to habitat modification and the effects of introduced species (*13*). In response to the crisis, two endemic lizard species were rescued into *ex situ* care in 2009, providing refuge from outright extinction before the last individuals were recorded in the wild in 2012 (*13*). In other cases, species were collected for scientific or hobbyist interest and only acquired conservation relevance once the situation in the wild subsequently became dire. For example, in 1925, 17 Socorro doves (*Zenaida graysoni*) were collected from Socorro Island in the Pacific Ocean and transported to an aviculturist in California, United States (*14*), forming the basis for an *ex situ* collection that is today distributed in small numbers in captive facilities across North America and Europe (*15*). On its native Socorro, however, the dove entered an abrupt decline sometime after 1958, and was last seen in the wild in 1972 (*15*, *16*). In other instances, collection into *ex situ* maintenance is itself the principal driver of extinction in the wild. Wild populations of Southern African cycad species such as the escarpment cycad (*Encephalartos brevifoliolatus*) and Heenan's cycad (*Encephalartos heenanii*) have disappeared due to collection for the trade in ornamental plants (*17*, *18*), yielding *ex situ* collections that nonetheless represent potential sources for eventual recovery in the wild.

Though the circumstances surrounding their procurement are diverse, these species share a dependence on human care, combined with a wild context that—historically at least—has presented threats sufficiently severe to lead to their extirpation.

EW species occupy a curiously overlooked space in the Red List, our framework for evaluating and comparing species' risk of extinction. The assessment process evaluates states and trends in the geographic ranges and populations of species, as well as their threats, and allocates categories of extinction risk accordingly. These categories range in increasing risk from "Least Concern" through "Near Threatened", "Vulnerable", "Endangered", "Critically Endangered", "Extinct in the Wild", and "Extinct". Species in the Vulnerable, Endangered, and Critically Endangered categories are classed as "threatened" with extinction. EW species are not, despite being categorised as facing higher extinction risk. In fact, because the Red List process concerns itself solely with wild populations, the populations of EW species—whether thriving or on the brink—are not subject to assessment. The broader conservation community has consequently largely ignored the extent of—and variation in—extinction risk among the very group of species for which humans are most responsible, and whose futures are amongst the least assured.

Here, harnessing global *ex situ* databases and the academic and grey literature, we reveal the dynamic and often perilous state occupied by EW species, assessing their current populations as well as summarising the journeys and fates of all species known to have been restricted to *ex situ* care since 1950. Extending our analysis beyond the introduction in 1994 of the EW category (*19*), we chose 1950 to approximate the beginning of the modern era of species conservation (*20*). This time window enabled us to build a comprehensive list of species in a comparable context, minimising the risk of biasing our selection towards well-known cases.

Our dataset therefore included the assessments of the 84 species (40 animals and 44 plants) categorized as EW on Red List version 2022-2 (*4*). Of these, two (both animals) have gone extinct since their most recent assessment (Table 1). The assessments of a further 10 appear erroneous: two are extinct having never been in *ex situ* care, three are likely extant in the wild having never been extirpated, three are synonyms of species that remain extant in the wild, and the statuses of two are unknown (Table S1). We added a further 21 species that were *ex situ*-restricted at some point since 1950, but now occupy a different state (i.e., they are either extinct or considered wild again). These species were identified through a review of the IUCN summary statistics for genuine status changes, the Red List narrative texts of extinct species, and the assessments of extant species with populations indicated as originating from reintroductions or assisted colonisations (*21*). Twelve of these additional species are now wild again (Table 2), and a further nine have gone extinct (Table 1). In total we identified and summarised the conservation history and statuses of 95 species (52 animals and 43 plants) known to have been EW or restricted to *ex situ* care since 1950, 72 of which (33 animals and 39 plants) are considered to remain in this state as of 2022.

For each species, we collected information on the history of the collection, *ex situ* maintenance, and conservation of each, namely: the periods over which founders of the *ex situ* population were collected from the wild; the number of individuals collected to initiate the *ex situ* population; the number of founder lineages represented in the present population (where this is noted as a separate number); the year the species was last recorded in the wild; and the timing and status of any attempts to re-establish the species in the wild through conservation translocations. The status of the *ex situ* populations of currently EW species was assessed by quantifying the number of institutions holding them; the type of institution for plants (i.e., botanical garden or seed bank); the total *ex situ* population size for animals (this is not generally quantified or reported for plants); whether an animal species was subject to metapopulation management or had a studbook; and whether any Population Viability Analyses (PVAs) had been carried out for *ex situ* populations. Data was collated primarily from Red List assessments, supplemented where necessary using recovery project documentation, academic literature, targeted Google and Google News searches, and contact with relevant taxon experts and conservation practitioners (*21*). Information on *ex situ* populations of currently EW species was derived from Species360's Zoological Information Management System (*22*), Association of Zoos and Aquariums' database of Species Survival Programs (SSPs) (*23*), the European Association of Zoos and Aquaria's list of EEPs (*24*), Australasia's Zoo Aquarium Association's list of Species Management Programs (SMPs) (*25*), and the World Association of Zoos and Aquariums' list of Global Species Management Plans (*26*) (for animal species) and Botanic Gardens Conservation International's PlantSearch (*27*) (for plant species).

THE VARIED AND WORRYING STATE OF EW SPECIES

We found considerable variation and alarming deficiencies amongst EW species in factors critical to their long-term recovery. A minimum of between 30 and 50 individuals is recommended to found an *ex situ* population to capture an adequate representation of the genetic diversity of the wild population (*28*, *29*). Most currently EW animal populations for which such information is available (eight of 13) were founded by fewer than 30 individuals, and amongst the less well documented plants we report that at least seven of 40 EW populations were founded by just a single individual (Table 3). Most *ex situ* populations of EW species were thus imperilled to begin with, and require population growth to enhance demographic security and reach a size at which loss through drift of the genetic diversity that remains is at a tolerably low level (Fig. 3A).

Of the 30 EW animal species currently maintained in *ex situ* institutions for which we could find data, only 6 have populations exceeding 1500 individuals, and half are below 500 (Fig. 1). Given that botanic gardens often hold just one or a few individuals of each species (*30*), we expect that the populations of EW plant species may be extremely small. What constitutes a viable population size is highly context specific, depending on the biology of the species, aspects of its management and environment, as well as varying definitions of "viable" (*31*). Viability can be expressed in demographic terms, for example the population size needed to have a specific probability of persistence over a specific period of time or number of generations. Meta-analyses of minimum viable population sizes calculated across hundreds of species have reported medians of 1377 (for a 90% probability of persistence over 100 years across 1198 animal and plant species) (*32*), 4169 (standardised to a 99% probability of persistence over 40 generations across 212 animal and plant species) (*33*), and 5816 (for a 99% probability of persistence over 40 generations across 102 vertebrate species) (*34*), with wide and positively-skewed distributions. Most EW species for which data on population sizes are available are well below these estimates. Though population viability analyses were at some point carried out for at least eight currently EW species (all animals), we are only aware of three that currently use these tools to inform management (Table S2).

Managers of *ex situ* populations must also consider the impact population size has on retention of genetic diversity. In situations such as those faced by EW species, where supplementation of populations with individuals from elsewhere (i.e., the wild) is impossible, an effective population size (N_e) of at least 500 is thought to be required for even well-founded populations to avert the loss of genetic diversity, and it has been argued that N_e = 1000 is a better approximation to maintain evolutionary potential (*35*). N_e corresponds to the number of individuals contributing to the next generation, and is generally considerably smaller than the total number of individuals in the population, the census population size (N). In *ex situ* populations of threatened animals, the ratio of effective population size to census population size (N_e/N) has been estimated to average 0.26 (*36*), implying that most populations should exceed 1900 individuals at the very least to maintain genetic diversity

(*37*). 80% of known populations of EW animals fall below this level, and half have census population sizes below even the minimum recommended N_e. These figures do not represent universal thresholds delineating viable populations from lost causes, but rather standards that enable us to highlight populations that may be at risk. In this light, the shortfall for EW species is stark.

Holding species across multiple collections provides a buffer against institutional-level risks such as disease outbreaks, catastrophes, and the financial insecurity and logistical challenges deepened by global crises such as the COVID-19 pandemic (*38*, *39*). Worryingly, most EW animal species are reported at four or fewer institutions (Fig. 2, Table S2). The median number of holders for an EW plant species is eight, but we note that six EW plant species are reported at just a single institution (Fig. 2, Table S2). Reassuringly, it is not the same few institutions holding these species: The 43 species with fewer than 10 holders are spread across 93 institutions (53 zoological and 40 botanical). Overall, EW species are held by at least 501 institutions globally (239 zoological and 262 botanical).

However, distributing an EW species across several holders brings with it the potential for fragmenting an already compromised population into a set of smaller isolated groups. For animal species, breeding and transfer between different institutions comprising *ex situ* metapopulations can be managed regionally under formalised breeding programs: EAZA *Ex situ* Programmes (EEPs) in Europe, Species Survival Plans (SSPs) predominantly in North America, and Species Management Programs (SMPs) in Australasia. Global Captive Management Programs (GCMPs) have been proposed in recognition of the need for overarching global management, but these have struggled to gain traction, and no EW species has a GCMP despite the fact that at least eight are held across multiple regions (*26*). Despite their benefits, we find that SSPs are absent for 50% (5/10) of those held at North American institutions, while EEPs are absent for 18% (5/22) of EW animal species held at European institutions (Table S2). Even for species covered by a cooperative breeding program, implementation of management decisions can be challenging. Based on logistical, husbandry, demographic, or genetic factors, SSPs issue recommendations to transfer individuals between institutions or for individuals to breed with a specific mate or mates. However, a recent analysis has found that SSP recommendations to transfer individuals between institutions were fulfilled just 57% of the time, while the fulfilment rate of recommendations for specific individuals to breed was even lower at 20% (*40*).

Genetic management is informed by a reliable understanding of the pedigree of individuals within a population, generally recorded in a studbook. We were unable to find any indication of studbooks for 31% (10/32) of EW animal species managed *ex situ* (Table S2). Species missing studbooks were fish, amphibians, and invertebrates, taxa typically housed and bred in groups, a situation in which individual pedigrees are generally unavailable. However, such species can still be subject to genetic management using population genetic models and group-level information (*41*), as is deployed for *ex situ* populations of Polynesian tree snails (*36*, *42*). Management of *ex situ* plant collections is hampered by poor knowledge of the provenance of populations, a limited ability to track them at an individual level, and a lack of coordination across institutions (*30*). Efforts to address these problems and develop pedigree-based metapopulation management techniques for plants are currently underway (*30*, *43*).

For some plant species, storage of propagules in seed banking facilities offers an opportunity to pause generational turnover, and thus circumvent many of the processes that compromise genetic viability of *ex situ* populations over time. Though not suitable for all species (*44*), this technique—which can retain seed viability for potentially hundreds of years (*45*)—will be crucial in ensuring that at least 75 per cent of threatened plant species are maintained *ex situ*, Target 8 of the Global Strategy for Plant Conservation (*46*). Using a seed storage prediction model (*21*, *47*), we found that approximately 89% (31 of 35 species modelled, see Table S5) of EW plant species are predicted to produce desiccation-tolerant seeds suitable for seed banking. While it is possible that some accessions from living collections may refer to seeds, it is striking that only 28% (11/39) of EW plant species are reported by dedicated seed banks (Fig. 2).

Beyond loss of diversity through genetic drift, maintaining species in *ex situ* care across multiple generations brings the risk of adaptation to the conditions in which the species is kept (*48*), a risk that increases with population size and genetic diversity (*38*). Further, even optimal *ex situ* care cannot prevent *in situ* change: plants and animals held separate from wild environments for extended periods may not be well adapted to the shifting ecosystems to which we would like to return them (*49*).

The state of EW species should thus be regarded with a sense of urgency. With small founder and population sizes and a modest number of holding institutions, most risk genetic deterioration, declines, and extinction under our care. *Ex situ* conservation has been instrumental in preventing extinction in these species, but it is not a tool that can forestall it indefinitely. Re-establishment in the wild is a crucial step towards their recovery.

CONTRASTING FATES: EXTINCTIONS VS RETURNS TO THE WILD.

We find that conservation translocations back to wild settings have been undertaken much less commonly for plant than animal species: only 26% (11/43) of historically (1950-2022) *ex situ*-restricted and 23% (9/39) of currently EW plant species, compared to the majority of both historically *ex situ*-restricted (32/53, 60%) and currently EW (22/33, 67%) animal species (Fig. 3, Tables 2, S2, and S4). The rate of translocations of plants from *ex situ* collections has been previously observed to be low (*11*), perhaps partly attributable to a lower level of attention and resource accorded to the conservation of plants when compared to that of animals (*50*). While the rate amongst animals is encouraging, overall we are still left with 41 extant EW species (30 plants and 11 animals) that have never been subject to an attempt at a return to the wild. The Socorro dove (*Zenaida graysoni*), for example, collected from the wild in 1925 (*14*), is approaching a century—approximately 37 generations—in *ex situ* care.

The EW state can nevertheless represent a crucial waypoint on the pathway to recovery. There are 12 species (10 animals and two plants) that were once extirpated from the wild but are now considered to have wild populations again (Fig. 3, Table 2). These include the Jaramago de Alborán (*Diplotaxis siettiana*), now categorized as Critically Endangered on the red list; the Yarkon bream (*Acanthobrama telavivensis*), which has been downlisted to Vulnerable; and the European Bison (*Bison bonasus*), which has recovered out of the threatened categories to Near Threatened. But less fortunate fates are also possible: 11 species have gone extinct after existing only in *ex situ* care (Fig 3, Table 1). These include the St Helena olive (*Nesiota elliptica*) and the Pinta giant tortoise (*Chelonoidis abingdonii*), both lost in the last decade.

THE NEED FOR AN IMPROVED SYSTEM OF ASSESSING *EX SITU*-RESTRICTED TAXA

Though we expanded our investigation of historically *ex situ*-restricted species beyond those assessed on the Red List as EW, we have deferred to the Red List in confirming present day extinction from the wild (*21*). This likely underrepresents the true number of species that currently merit the status or are approaching it. For example, a further 58 species (46 plants and 12 animals) currently assessed as Critically Endangered have been tagged as “Possibly Extinct in the Wild” (*4*, *51*). In addition, the often slow pace of changes in Red List status

(*52*) combines with a conservative approach to declaring extinction (*53*) to produce a considerable lag between a species last being seen in the wild and it first being listed as EW: we find 11 years to be the median interval. Bearing in mind the threat of an oncoming wave of extinctions over the coming decades (*54*), a considerable number of *ex situ*-restricted species may therefore be accumulating with no reliable way of identifying them. Species that have recently been claimed to probably qualify as EW but are not yet assessed as such include the ʻālula (*Brighamia insignis*) (*43*), a shrub native to Hawaii, the Vietnam pheasant (*Lophura edwardsi*) (*55*), and the Javan pied starling (*Gracupica jalla*) (*56*), all of which are classified as Critically Endangered, but only the first bearing the "Possibly Extinct in the Wild" tag.

It is clear, however, that designation as EW would not facilitate the evaluation of extinction risk or recovery potential. As is demonstrated in this study, the single EW category contains such variability in the viability of its species (and efforts to quantify that viability) as to potentially conceal the plight of the least secure. Might the Catarina pupfish (*Megupsilon aporus*) be with us today had its precarious status in the years running up to its demise been better characterised and communicated (*57*)? It is certainly not credible to place such a species in the same category of extinction risk as, say, the milu (Père David's deer, *Elaphurus davidianus*) which, after over 35 years of reintroductions and conservation management, numbers over 9000 individuals of varying degrees of "wildness" distributed across its native range in China (*58*) while still being assessed as EW. An improved system for assessing the health and progress of EW species would be both beneficial and—given that the global databases that could inform such surveillance are already established—feasible.

RECOMMENDATIONS

The cases we depict chart more than 70 years of attempts to use *ex situ* conservation to prevent extinction and facilitate the recovery of species on the very brink, highlighting both the fragility of this status and the potential for success despite that fragility. Ensuring that the fortunes of EW species continue to bend away from extinction requires a redoubling of effort and a collective realisation—in the minds of the conservation community, legislators, and the public—of their existence and plight. In response, the IUCN World Conservation Congress 2020 called for the re-establishment of current EW species in the wild by 2030 (*59*). This should be coupled with the identification of further currently threatened species whose recovery could be achieved through *ex situ* care. We urge a forward-looking approach to rescue, revitalize, release, and reinforce populations: rescue suitable species close to extinction into *ex situ* care, revitalise and strengthen current *ex situ* populations to ensure continued viability, engage in ambitious and innovative release programs to return species to the wild, and drive recovery of released populations through continued reinforcement and management.

Deciding where, when, and whether to rescue species is not a trivial task and is confounded by risky (that is uncertain) outcomes and strong emotions. From a biological perspective, the removal of a species to *ex situ* care may be challenging such that the attempt accelerates extinction and, combined with downstream consideration of the likelihood of successful wild releases from *ex situ* care, should be weighed against *in situ* alternatives (*60*). Decisions about rescue will always go beyond biological perspectives to include a mix of financial, ethical, social and cultural considerations. For example, at least four Hawaiian forest bird species face extinction in the coming decade as a result of avian malaria (*61*). The immediate removal of individuals into *ex situ* care, and thus the likely creation of EW populations, is seen as the management action with the highest probability of extinction avoidance for at least one of these species, the ʻakikiki (*Oreomystis bairdi*), with an estimated wild population in 2021 of just 45 individuals (*61*). The location of *ex situ* facilities must balance Native Hawaiians' preference not to remove birds from Hawai'i (*61*). Such multi-objective decisions are inevitable in conservation and influence what alternatives are available and how a best one is selected. We encourage adopting a transparent and deliberative approach to decision making on a case by case basis, such that values are clearly identified and decisions are rationally made in light of these (*62*). We must be bold and take urgent risky action, but this does not mean abandoning critically important recognition of values and drawing on available science to inform what this action is and how we best implement it. We wish to avoid cases such as the Christmas Island pipistrelle (*Pipistrellus murrayi*), for which *ex situ* care was proposed and eventually agreed upon, but, through delay and indecision, inaction and extinction became the action inadvertently chosen (*63*).

Similarly, *ex situ* institutions such as zoos and botanic gardens must balance multiple values, of which EW species conservation is just one. In most cases, revitalisation of *ex situ* EW populations will require significant additional resources: more individuals require more space, infrastructure, and staff time. This must be balanced with the contributions *ex situ* institutions also play in non-EW species conservation, education, visitor experience and the space and financial constraints required to deliver these. Whilst we are indebted to such institutions for being the only things standing between EW species and extinction, we encourage a much more strategic approach to EW species *ex situ* care whereby decision science is used to develop unified management plans informed, at the least, by population viability analysis and genetic management. In addition, we call on funders to support the delivery of *ex situ* care and consequent recovery in the wild via release and reinforcement.

As recovery in the wild ought to be an ultimate objective for all EW species, management plans for *ex situ* populations should be integrated with *in situ* planning, as is envisaged in the IUCN's "One Plan Approach" (*64*), which has not, as far as we can identify, been adopted for any EW species. There are many reasons why some EW species have never been released into the wild. For some plants, such as the seven EW *Brugmansia* species native to South America, historic wild localities are simply not known (*65*). For some species, such as the sihek (or Guam kingfisher, *Todiramphus cinnamominus*), their indigenous range remains inhospitable to their return. However, reasoned and bold actions may allow wild recovery either through proactive removal of *in situ* extinction drivers, or releases beyond indigenous range (*66*, *67*). For example, Christmas Island blue-tailed skinks (*Cryptoblepharus egeriae*) have been released to the wild on the Cocos (Keeling) islands (*68*) and proposals for sihek releases on Palmyra Atoll are under consideration (*69*). Whilst release is a landmark moment—and is rightly celebrated—this should typically mark the beginning of a long-term commitment to recover the species *in situ*. Pioneering work has returned 10 formerly-extirpated Polynesian tree snail species to the Society Islands, but considerable obstacles to the recovery of many of these species remain in part due to the ongoing threats posed by the non-native predatory New Guinea flatworm (*Platydemus manokwari*) (*70*). Rather than give up, those involved in Polynesian tree snail recovery are learning and modifying how to best attempt new releases and reinforce all wild populations. With sustained support and adaptive management, the Polynesian tree snails and others can emulate the successful paths back to recovery in the wild forged by species such as the Yarkon bream and European bison.

Real opportunities to prevent extinction and return previously lost species to the wild abound. We must take them.

References

1. H. M. Pereira, P. W. Leadley, V. Proença, R. Alkemade, J. P. W. Scharlemann, J. F. Fernandez-Manjarrés, M. B. Araújo, P. Balvanera, R. Biggs, W. W. L. Cheung, L. Chini, H. D. Cooper, E. L. Gilman, S. Guénette, G. C. Hurtt, H. P. Huntington, G. M. Mace, T. Oberdorff, C. Revenga, P. Rodrigues, R. J. Scholes, U. R. Sumaila, M. Walpole, Scenarios for Global Biodiversity in the 21st Century. *Science*. **330**, 1496–1501 (2010).

2. CBD, "Global Biodiversity Outlook 5. Montreal." (2020).

3. G. Ceballos, P. R. Ehrlich, A. D. Barnosky, A. García, R. M. Pringle, T. M. Palmer, Accelerated modern human–induced species losses: Entering the sixth mass extinction. *Sci. Adv.* **1**, e1400253 (2015).

4. IUCN, The IUCN Red List of Threatened Species. *IUCN Red List Threat. Species Version 2022-2* (2022), (available at https://www.iucnredlist.org/en).

5. R. Dirzo, H. S. Young, M. Galetti, G. Ceballos, N. J. B. Isaac, B. Collen, Defaunation in the Anthropocene. *Science*. **345**, 401–406 (2014).

6. C. Régnier, G. Achaz, A. Lambert, R. H. Cowie, P. Bouchet, B. Fontaine, Mass extinction in poorly known taxa. *Proc. Natl. Acad. Sci.* **112**, 7761–7766 (2015).

7. G. Ceballos, P. R. Ehrlich, P. H. Raven, Vertebrates on the brink as indicators of biological annihilation and the sixth mass extinction. *Proc. Natl. Acad. Sci.* (2020), doi:10.1073/pnas.1922686117.

8. CBD, Kunming-Montreal Global biodiversity framework (2022), (available at https://www.cbd.int/doc/c/e6d3/cd1d/daf663719a03902a9b116c34/cop-15-l-25-en.pdf).

9. M. Hoffmann, C. Hilton-Taylor, A. Angulo, M. Böhm, T. M. Brooks, S. H. M. Butchart, K. E. Carpenter, J. Chanson, B. Collen, N. A. Cox, W. R. T. Darwall, N. K. Dulvy, L. R. Harrison, V. Katariya, C. M. Pollock, S. Quader, N. I. Richman, A. S. L. Rodrigues, M. F. Tognelli, J.-C. Vié, J. M. Aguiar, D. J. Allen, G. R. Allen, G. Amori, N. B. Ananjeva, F. Andreone, P. Andrew, A. L. A. Ortiz, J. E. M. Baillie, R. Baldi, B. D. Bell, S. D. Biju, J. P. Bird, P. Black-Decima, J. J. Blanc, F. Bolaños, W. Bolivar-G, I. J. Burfield, J. A. Burton, D. R. Capper, F. Castro, G. Catullo, R. D. Cavanagh, A. Channing, N. L. Chao, A. M. Chenery, F. Chiozza, V. Clausnitzer, N. J. Collar, L. C. Collett, B. B. Collette, C. F. C. Fernandez, M. T. Craig, M. J. Crosby, N. Cumberlidge, A. Cuttelod, A. E. Derocher, A. C. Diesmos, J. S. Donaldson, J. W. Duckworth, G. Dutson, S. K. Dutta, R. H. Emslie, A. Farjon, S. Fowler, J. Freyhof, D. L. Garshelis, J. Gerlach, D. J. Gower, T. D. Grant, G. A. Hammerson, R. B. Harris, L. R. Heaney, S. B. Hedges, J.-M. Hero, B. Hughes, S. A. Hussain, J. I. M, R. F. Inger, N. Ishii, D. T. Iskandar, R. K. B. Jenkins, Y. Kaneko, M. Kottelat, K. M. Kovacs, S. L. Kuzmin, E. L. Marca, J. F. Lamoreux, M. W. N. Lau, E. O. Lavilla, K. Leus, R. L. Lewison, G. Lichtenstein, S. R. Livingstone, V. Lukoschek, D. P. Mallon, P. J. K. McGowan, A. McIvor, P. D. Moehlman, S. Molur, A. M. Alonso, J. A. Musick, K. Nowell, R. A. Nussbaum, W. Olech, N. L. Orlov, T. J. Papenfuss, G. Parra-Olea, W. F. Perrin, B. A. Polidoro, M. Pourkazemi, P. A. Racey, J. S. Ragle, M. Ram, G. Rathbun, R. P. Reynolds, A. G. J. Rhodin, S. J. Richards, L. O. Rodríguez, S. R. Ron, C. Rondinini, A. B. Rylands, Y. S. de Mitcheson, J. C. Sanciangco, K. L. Sanders, G. Santos-Barrera, J. Schipper, C. Self-Sullivan, Y. Shi, A. Shoemaker, F. T. Short, C. Sillero-Zubiri, D. L. Silvano, K. G. Smith, A. T. Smith, J. Snoeks, A. J. Stattersfield, A. J. Symes, A. B. Taber, B. K. Talukdar, H. J. Temple, R. Timmins, J. A. Tobias, K. Tsytsulina, D. Tweddle, C. Ubeda, S. V. Valenti, P. P. van Dijk, L. M. Veiga, A. Veloso, D. C. Wege, M. Wilkinson, E. A. Williamson, F. Xie, B. E. Young, H. R. Akçakaya, L. Bennun, T. M. Blackburn, L. Boitani, H. T. Dublin, G. A. B. da Fonseca, C. Gascon, T. E. Lacher, G. M. Mace, S. A. Mainka, J. A. McNeely, R. A. Mittermeier, G. M. Reid, J. P. Rodriguez, A. A. Rosenberg, M. J. Samways, J. Smart, B. A. Stein, S. N. Stuart, The Impact of Conservation on the Status of the World's Vertebrates. *Science*. **330**, 1503–1509 (2010).

10. F. C. Bolam, L. Mair, M. Angelico, T. M. Brooks, M. Burgman, C. Hermes, M. Hoffmann, R. W. Martin, P. J. K. McGowan, A. S. L. Rodrigues, C. Rondinini, J. R. S. Westrip, H. Wheatley, Y. Bedolla-Guzmán, J. Calzada, M. F. Child, P. A. Cranswick, C. R. Dickman, B. Fessl, D. O. Fisher, S. T. Garnett, J. J. Groombridge, C. N. Johnson, R. J. Kennerley, S. R. B. King, J. F. Lamoreux, A. C. Lees, L. Lens, S. P. Mahood, D. P. Mallon, E. Meijaard, F. Méndez-Sánchez, A. R. Percequillo, T. J. Regan, L. M. Renjifo, M.

C. Rivers, N. S. Roach, L. Roxburgh, R. J. Safford, P. Salaman, T. Squires, E. Vázquez-Domínguez, P. Visconti, J. C. Z. Woinarski, R. P. Young, S. H. M. Butchart, How many bird and mammal extinctions has recent conservation action prevented? *Conserv. Lett.* (2020), doi:10.1111/conl.12762.

11. T. Abeli, S. Dalrymple, S. Godefroid, A. Mondoni, J. V. Müller, G. Rossi, S. Orsenigo, Ex situ collections and their potential for the restoration of extinct plants. *Conserv. Biol.* **34**, 303–313 (2020).

12. IUCN, *IUCN Red List Categories and Criteria: Version 3.1* (IUCN, Gland, Switzerland and Cambridge, UK, Second edition., 2012).

13. P. Andrew, H. Cogger, D. Driscoll, S. Flakus, P. Harlow, D. Maple, M. Misso, C. Pink, K. Retallick, K. Rose, B. Tiernan, J. West, J. C. Z. Woinarski, Somewhat saved: a captive breeding programme for two endemic Christmas Island lizard species, now extinct in the wild. *Oryx*. **52**, 171–174 (2018).

14. E. W. Gifford, Grayson's Pigeon (Zenaidura graysoni) in Captivity. *The Auk*. **44**, 513–519 (1927).

15. BirdLife International, Zenaida graysoni. *IUCN Red List Threat. Species* (2020) (available at https://dx.doi.org/10.2305/IUCN.UK.2020-3.RLTS.T22690740A178409463.en).

16. L. F. Baptista, Socorro Dove Breeding/Release Program. *AFA Watchb.* **18**, 15–16 (1991).

17. J. D. W. Bösenberg, Encephalartos brevifoliolatus. *IUCN Red List Threat. Species* (2022) (available at https://dx.doi.org/10.2305/IUCN.UK.2022-1.RLTS.T41882A50824805.en).

18. J. D. W. Bösenberg, Encephalartos heenanii. *IUCN Red List Threat. Species* (2022) (available at https://dx.doi.org/10.2305/IUCN.UK.2022-1.RLTS.T41888A51055983.en).

19. B. Groombridge, G. M. Mace, G. Rabb, 1994 IUCN red list of threatened animals (1994).

20. H. R. Akçakaya, E. L. Bennett, T. M. Brooks, M. K. Grace, A. Heath, S. Hedges, C. Hilton-Taylor, M. Hoffmann, D. A. Keith, B. Long, D. P. Mallon, E. Meijaard, E. J. Milner-Gulland, A. S. L. Rodrigues, J. P. Rodriguez, P. J. Stephenson, S. N. Stuart, R. P. Young, Quantifying species recovery and conservation success to develop an IUCN Green List of Species. *Conserv. Biol.* **32**, 1128–1138 (2018).

21. Materials and methods are available as supplementary materials.

22. Species360 Zoological Information Management System (ZIMS) (2022), (available at https://www.species360.org/).

23. AZA, Animal Program Database (2022), (available at https://ams.aza.org/eweb/DynamicPage.aspx?Site=AZA&WebKey=8f652949-31be-4387-876f-f49a2d7263b2).

24. PROGRAMMES » EAZA, (available at https://www.eaza.net/conservation/programmes/##TAGSandBP).

25. Species Programs, (available at https://zooaquarium.org.au/public/Public/Conservation/Species-Programs.aspx).

26. Global Species Management Plans - WAZA. *https://www.waza.org/*, (available at https://www.waza.org/priorities/conservation/conservation-breeding-programmes/global-species-management-plans/).

27. BGCI, PlantSearch online database. *Bot. Gard. Conserv. Int.* (2022), (available at https://www.bgci.org/resources/bgci-databases/plantsearch/).

28. F. W. Allendorf, G. Luikart, *Conservation and the Genetics of Populations* (John Wiley & Sons, 2009).

29. R. Frankham, J. D. Ballou, D. A. Briscoe, *Introduction to Conservation Genetics* (Cambridge University Press, Cambridge, ed. 2, 2010; https://www.cambridge.org/core/books/introduction-to-conservation-genetics/696B4E558C93F7FBF9C33D6358EA7425).

30. J. Wood, J. D. Ballou, T. Callicrate, J. B. Fant, M. P. Griffith, A. T. Kramer, R. C. Lacy, A. Meyer, S. Sullivan, K. Traylor-Holzer, S. K. Walsh, K. Havens, Applying the zoo model to conservation of threatened exceptional plant species. *Conserv. Biol.* **34**, 1416–1425 (2020).

31. R. C. Lacy, Lessons from 30 years of population viability analysis of wildlife populations. *Zoo Biol.* **38**, 67–77 (2019).

32. B. W. Brook, L. W. Traill, C. J. A. Bradshaw, Minimum viable population sizes and global extinction risk are unrelated. *Ecol. Lett.* **9**, 375–382 (2006).

33. L. W. Traill, C. J. A. Bradshaw, B. W. Brook, Minimum viable population size: A meta-analysis of 30 years of published estimates. *Biol. Conserv.* **139**, 159–166 (2007).

34. D. H. Reed, J. J. O'Grady, B. W. Brook, J. D. Ballou, R. Frankham, Estimates of minimum viable population sizes for vertebrates and factors influencing those estimates. *Biol. Conserv.* **113**, 23–34 (2003).

35. R. Frankham, C. J. A. Bradshaw, B. W. Brook, Genetics in conservation management: Revised recommendations for the 50/500 rules, Red List criteria and population viability analyses. *Biol. Conserv.* **170**, 56–63 (2014).

36. R. Frankham, J. D. Ballou, D. A. Briscoe, *Introduction to Conservation Genetics* (Cambridge University Press, Cambridge, 2002; https://www.cambridge.org/core/books/introduction-to-conservation-genetics/F1F8EDB8B86A1790A406064296878B23).

37. C. M. Lees, J. Wilcken, Sustaining the Ark: the challenges faced by zoos in maintaining viable populations. *Int. Zoo Yearb.* **43**, 6–18 (2009).

38. R. Frankham, Genetic adaptation to captivity in species conservation programs. *Mol. Ecol.* **17**, 325–333 (2008).

39. A. Trask, S. Canessa, A. Moehrenschlager, S. Newland, S. Medina, J. Ewen, Extinct-in-the-wild species' last stand. *Science*. **369**, 516–516 (2020).

40. L. J. Faust, S. T. Long, K. Perišin, J. L. Simonis, Uncovering challenges to sustainability of AZA Animal Programs by evaluating the outcomes of breeding and transfer recommendations with PMCTrack. *Zoo Biol.* **38**, 24–35 (2019).

41. J. Wang, Monitoring and managing genetic variation in group breeding populations without individual pedigrees. *Conserv. Genet.* **5**, 813–825 (2004).

42. D. Clarke, "EAZA Best Practice Guidelines for Partula snails" (EAZA, 2019), (available at https://www.eaza.net/assets/Uploads/CCC/BPG-2019/2019-Partula-sp-EAZA-Best-Practice-Guidelines-Approved.pdf).

43. J. A. Foster, S. K. Walsh, K. Havens, A. T. Kramer, J. B. Fant, Supporting long-term sustainability of ex situ collections using a pedigree-based population management approach. *Appl. Plant Sci.*, e11491 (2022).

44. S. V. Wyse, J. B. Dickie, K. J. Willis, Seed banking not an option for many threatened plants. *Nat. Plants*. **4**, 848–850 (2018).

45. K. O'Donnell, S. Sharrock, The contribution of botanic gardens to ex situ conservation through seed banking. *Plant Divers.* **39**, 373–378 (2017).

46. S. Sharrock, "Plant Conservation Report 2020: A review of progress in implementation of the Global Strategy for Plant Conservation 2011-2020." (Secretariat of the Convention on Biological Diversity,

Montréal, Canada and Botanic Gardens Conservation International, Richmond, UK., 2020), (available at https://www.cbd.int/doc/publications/cbd-ts-95-en-hr.pdf).

47. S. V. Wyse, J. B. Dickie, Taxonomic affinity, habitat and seed mass strongly predict seed desiccation response: a boosted regression trees analysis based on 17 539 species. *Ann. Bot.* **121**, 71–83 (2018).

48. R. Rauschkolb, L. Szczeparska, A. Kehl, O. Bossdorf, J. F. Scheepens, Plant populations of three threatened species experience rapid evolution under ex situ cultivation. *Biodivers. Conserv.* **28**, 3951–3969 (2019).

49. D. J. Schoen, A. H. D. Brown, The Conservation of Wild Plant Species in Seed Banks: Attention to both taxonomic coverage and population biology will improve the role of seed banks as conservation tools. *BioScience*. **51**, 960–966 (2001).

50. V. Negrón-Ortiz, Pattern of expenditures for plant conservation under the Endangered Species Act. *Biol. Conserv.* **171**, 36–43 (2014).

51. S. H. Butchart, A. J. Stattersfield, T. M. Brooks, Going or gone: defining "Possibly Extinct" species to give a truer picture of recent extinctions. *Bull.-Br. Ornithol. Club*. **126**, 7 (2006).

52. S. H. M. Butchart, A. J. Stattersfield, L. A. Bennun, S. M. Shutes, H. R. Akçakaya, J. E. M. Baillie, S. N. Stuart, C. Hilton-Taylor, G. M. Mace, Measuring Global Trends in the Status of Biodiversity: Red List Indices for Birds. *PLOS Biol.* **2**, e383 (2004).

53. S. H. M. Butchart, S. Lowe, R. W. Martin, A. Symes, J. R. S. Westrip, H. Wheatley, Which bird species have gone extinct? A novel quantitative classification approach. *Biol. Conserv.* **227**, 9–18 (2018).

54. M. J. Monroe, S. H. M. Butchart, A. O. Mooers, F. Bokma, The dynamics underlying avian extinction trajectories forecast a wave of extinctions. *Biol. Lett.* **15**, 20190633 (2019).

55. N. J. Collar, Preparing captive-bred birds for reintroduction: the case of the Vietnam Pheasant Lophura edwardsi. *Bird Conserv. Int.* **30**, 559–574 (2020).

56. S. (Bas) van Balen, N. J. Collar, The Vanishing Act: A History and Natural History of the Javan Pied Starling Gracupica jalla. *Ardea*. **109**, 41–54 (2021).

57. R. da Silva, P. Pearce-Kelly, B. Zimmerman, M. Knott, W. Foden, D. A. Conde, Assessing the conservation potential of fish and corals in aquariums globally. *J. Nat. Conserv.* **48**, 1–11 (2019).

58. Z. Cheng, X. Tian, Z. Zhong, P. Li, D. Sun, J. Bai, Y. Meng, S. Zhang, Y. Zhang, L. Wang, D. Liu, Reintroduction, distribution, population dynamics and conservation of a species formerly extinct in the wild: A review of thirty-five years of successful Milu (Elaphurus davidianus) reintroduction in China. *Glob. Ecol. Conserv.*, e01860 (2021).

59. IUCN, 119 - Improving process and action to identify and recover 'Extinct in the Wild' species. *IUCN World Conserv. Congr. 2020* (2020), (available at https://www.iucncongress2020.org/motion/119).

60. S. Canessa, S. J. Converse, M. West, N. Clemann, G. Gillespie, M. McFadden, A. J. Silla, K. M. Parris, M. A. McCarthy, Planning for ex situ conservation in the face of uncertainty. *Conserv. Biol.* **30**, 599–609 (2016).

61. E. H. Paxton, M. Laut, S. Enomoto, M. Bogardus, "Hawaiian forest bird conservation strategies for minimizing the risk of extinction: biological and biocultural considerations. Hawai'i Cooperative Studies Unit Technical Report HCSU-103" (University of Hawai'i at Hilo, Hawaii, USA, 2022), (available at http://hdl.handle.net/10790/5386).

62. V. Hemming, A. E. Camaclang, M. S. Adams, M. Burgman, K. Carbeck, J. Carwardine, I. Chadès, L. Chalifour, S. J. Converse, L. N. K. Davidson, G. E. Garrard, R. Finn, J. R. Fleri, J. Huard, H. J. Mayfield, E. M. Madden, I. Naujokaitis-Lewis, H. P. Possingham, L. Rumpff, M. C. Runge, D. Stewart, V. J. D.

Tulloch, T. Walshe, T. G. Martin, An introduction to decision science for conservation. *Conserv. Biol.* **36**, e13868 (2022).

63. T. G. Martin, S. Nally, A. A. Burbidge, S. Arnall, S. T. Garnett, M. W. Hayward, L. F. Lumsden, P. Menkhorst, E. McDonald-Madden, H. P. Possingham, Acting fast helps avoid extinction. *Conserv. Lett.* **5**, 274–280 (2012).

64. O. Byers, C. Lees, J. Wilcken, C. Schwitzer, The One Plan Approach: The philosophy and implementation of CBSG's approach to integrated species conservation planning. *WAZA Mag.* **14**, 2–5 (2013).

65. A. Hay, IUCN Red List of Threatened Species: Brugmansia aurea. *IUCN Red List Threat. Species* (2014) (available at https://www.iucnredlist.org/en).

66. IUCN/SSC, *Guidelines for reintroductions and other conservation translocations.* (2013; http://data.iucn.org/dbtw-wpd/edocs/2013-009.pdf).

67. J. F. Brodie, S. Lieberman, A. Moehrenschlager, K. H. Redford, J. P. Rodríguez, M. Schwartz, P. J. Seddon, J. E. M. Watson, Global policy for assisted colonization of species. *Science*. **372**, 456–458 (2021).

68. Parks Australia, Basking on tropical oasis after decade in captivity (2021), (available at https://parksaustralia.gov.au/christmas/news/basking-on-tropical-oasis-after-decade-in-captivity/).

69. Endangered and Threatened Wildlife and Plants; Establishment of a Nonessential Experimental Population of the Guam Kingfisher, or Sihek, on Palmyra Atoll, USA. *Fed. Regist.* (2022), (available at https://www.federalregister.gov/documents/2022/08/31/2022-18571/endangered-and-threatened-wildlife-and-plants-establishment-of-a-nonessential-experimental).

70. T. Coote, G. Garcia, D. Clarke, Fourth year of Partula species reintroductions into natural habitat on Tahiti and Moorea. *Tentacle*, 35–38 (2019).

71. Smith et al 2023 Extinct in the Wild data, , doi:10.5281/zenodo.7534501.

72. E. VanderWerf, The Race to Save the World's Rarest Bird: The Discovery and Death of the Po'ouli. *The Auk*. **127**, 958–959 (2010).

73. Nesiota elliptica (Roxb.) Hook.f. *Plants World Online*, (available at http://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:717646-1).

74. J. Gerlach, Partula arguta, (available at https://islandbiodiversity.com/arguta.htm).

75. J. Randerson, End of the trail for Polynesia's star snails. *New Sci.* **178**, 10–10 (2003).

76. J. Murray, E. Murray, M. S. Johnson, B. Clarke, The extinction of Partula on Moorea (1988).

77. S. Wells, The extinction of endemic snails (genus Partula) in French Polynesia: is captive breeding the only solution. *Conserv. Biol. Molluscs IUCN Species Surviv. Comm. World Conserv. Union*, 25–28 (1995).

78. S. Tonge, Q. Bloxam, A review of the captive-breeding programme for Polynesian tree snails Partula spp. *Int. Zoo Yearb.* **30**, 51–59 (1991).

79. A. A. Cunningham, P. Daszak, Extinction of a Species of Land Snail Due to Infection with a Microsporidian Parasite. *Conserv. Biol.* **12**, 1139–1141 (1998).

80. M. Goren, Saving critically endangered fish species–utopia or practical idea? The story of the Yarqon bleak–Acanthobrama telavivensis (Cyprinidae) as a test case. *Aqua Int. J. Ichthyol.* **15**, 1–12 (2009).

81. Z. Pucek, IUCN/SSC Bison Specialist Group, International Union for Conservation of Nature and Natural Resources, Eds., *European bison: status survey and conservation action plan* (IUCN, Gland, Switzerland ; Cambridge, 2004).

82. M. Tokarska, C. Pertoldi, R. Kowalczyk, K. Perzanowski, Genetic status of the European bison Bison bonasus after extinction in the wild and subsequent recovery. *Mammal Rev.* **41**, 151–162 (2011).

83. J. W. Hinton, M. J. Chamberlain, D. R. Rabon, Red Wolf (Canis rufus) Recovery: A Review with Suggestions for Future Research. *Animals*. **3**, 722–744 (2013).

84. J. P. Gibbs, E. A. Hunter, K. T. Shoemaker, W. H. Tapia, L. J. Cayot, Demographic Outcomes and Ecosystem Implications of Giant Tortoise Reintroduction to Española Island, Galapagos. *PLOS ONE*. **9**, e110742 (2014).

85. W. Tapia, H. B. Goldspiel, J. P. Gibbs, Introduction of giant tortoises as a replacement "ecosystem engineer" to facilitate restoration of Santa Fe Island, Galapagos. *Restor. Ecol.* **30**, e13476 (2022).

86. S. Wakefield, J. Knowles, W. Zimmermann, M. Dierendonck, Status and Action Plan for the Przewalski's Horse (Equus ferus przewalskii). *Equids Zebras Asses Horses Status Surv. Conserv. Action Plan* (2002).

87. J. R. Walters, S. R. Derrickson, D. M. Fry, S. M. Haig, J. M. Marzluff, J. M. W. Jr, Status of the California Condor (Gymnogyps californianus) and Efforts to Achieve Its Recovery. *The Auk*. **127**, 969–1001 (2010).

88. T. Belfield, T. Tunison, J. Chase, S. McDaniel, "Rare plant stabilization projects at Hawaii Volcanoes National Park, 1998-2008" (Technical Report 174, Pacific Cooperative Studies Unit, University of Hawai`i, Honolulu, Hawai`i, 2011), p. 121.

89. M. K. Brock, G. M. Beauprez, The Rail Road To Recovery. *Endanger. Species Update*. **18**, S6–S6 (2001).

90. ETWP; Determination of Experimental Population Status for an Introduced Population of Guam Rails on Rota in the Commonwealth of the Northern Mariana Islands; 54 FR 43966 43970 | U.S. Fish & Wildlife Service. *FWS.gov* (1989), (available at https://www.fws.gov/species-publication-action/etwp-determination-experimental-population-status-introduced-0).

91. A. Spalton, A brief history of the reintroduction of the Arabian oryx Oryx leucoryx into Oman 1980–1992. *Int. Zoo Yearb.* **32**, 81–90 (1993).

92. J. Roelle, B. Miller, J. Godbey, D. Biggins, Recovery of the black-footed ferret: progress and continuing challenges. *U. S. Geol. Surv. Sci. Investig. Rep.* **5293** (2005).

93. T. Nakabo, K. Nakayama, N. Muto, M. Miyazawa, Oncorhynchus kawamurae "Kunimasu," a deepwater trout, discovered in Lake Saiko, 70 years after extinction in the original habitat, Lake Tazawa, Japan. *Ichthyol. Res.* **58**, 180–183 (2011).

94. WFO, *World Flora Online Version 2022 07* (2022), (available at http://www.worldfloraonline.org/).

95. Agave vera-cruz Mill. | Plants of the World Online | Kew Science. *Plants World Online*, (available at http://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:62336-1).

96. USFWS, "Cyrtandra waiolani (ha'iwale) 5-Year Review Summary and Evaluation" (2019), (available at https://ecos.fws.gov/docs/tess/species_nonpublish/2789.pdf).

97. V. Tatayah, R. Jhangeer-Khan, J. A. Bégué, Dombeya rodriguesiana. IUCN Red List of Threatened Species: *IUCN Red List Threat. Species* (2021) (available at https://www.iucnredlist.org/en).

98. S. M. Toledo-Castro, J. A. González-Lavaut, O. Echemendí, N. García-González, Phytochemical and pharmacological evaluation of the fruits of Erythroxylum minutifolium Griseb. (Erythroxylaceae). *Rev. Cuba. Plantas Med.* **13** (2008).

99. B. Lang, D. Kelt, S. Shuster, The role of controlled propagation on an endangered species: Demographic effects of habitat heterogeneity among captive and native populations of the Socorro isopod (Crustacea: Flabellifera). *Biodivers. Conserv.* **15**, 3909–3935 (2006).

100. J. Li, H. Du, J. Wu, H. Zhang, L. Shen, Q. Wei, Foundation and Prospects of Wild Population Reconstruction of Acipenser dabryanus. *Fishes*. **6**, 55 (2021).

101. USFWS, "Wyoming Toad Bufo hemiophrys baxteri now known as Anaxyrus baxteri Revised Recovery Plan, May 2015; Original Approved September 11, 1991." (U.S. Fish and Wildlife Service, Cheyenne, Wyoming, 2015).

102. P. E. A. Hoeck, M. E. Wolak, R. A. Switzer, C. M. Kuehler, A. A. Lieberman, Effects of inbreeding and parental incubation on captive breeding success in Hawaiian crows. *Biol. Conserv.* **184**, 357–364 (2015).

103. ʻAlalā Project, Press Release: Adaptation is key to overcoming challenges faced in ʻAlalā Recovery program (2020), (available at https://dlnr.hawaii.gov/alalaproject/2020/10/06/press-release-adaptation-is-key-to-overcoming-challenges-faced-in-%ca%bbalala-recovery-program/).

104. J.-P. Emery, thesis, University of Western Australia (2021).

105. R. McKie, 'Extinct' parrots make a flying comeback in Brazil. *The Observer* (2022), (available at https://www.theguardian.com/environment/2022/jul/10/extinct-parrots-make-a-flying-comeback-in-brazil).

106. S. Contreras Balderas, "Conservation of Mexican freshwater fishes: Some protected sites and species, and recent federal legislation" in *Battle against extinction. Native fish management in the American West*, W. L. Minckley, J. E. Deacon, Eds. (University of Arizona Press, 1991), pp. 191–197.

107. S. T. Turvey, I. Barnes, M. Marr, S. Brace, Imperial trophy or island relict? A new extinction paradigm for Père David's deer: a Chinese conservation icon. *R. Soc. Open Sci.* **4**, 171096 (2017).

108. M. C. Costa, P. R. R. O. Jr, P. V. Davanço, C. de Camargo, N. M. Laganaro, R. A. Azeredo, J. Simpson, L. F. Silveira, M. R. Francisco, Recovering the Genetic Identity of an Extinct-in-the-Wild Species: The Puzzling Case of the Alagoas Curassow. *PLOS ONE*. **12**, e0169636 (2017).

109. P. Biondi, Extinct in the wild, a Brazilian bird makes a tentative return to the jungle. *Mongabay Environ. News* (2019), (available at https://news.mongabay.com/2019/12/extinct-in-the-wild-a-brazilian-bird-makes-a-tentative-return-to-the-jungle/).

110. S. Lee, K. Zippel, L. Ramos, J. Searle, Captive-breeding programme for the Kihansi spray toad Nectophrynoides asperginis at the Wildlife Conservation Society, Bronx, New York. *Int. Zoo Yearb.* **40**, 241–253 (2006).

111. C. Mgina, The Dynamics of Re-introduced Kihansi Spray Toad Nectophrynoides asperginis and other Amphibians in Kihansi Gorge, Udzungwa Mountains, Tanzania. *Tanzan. J. Sci.* **45**, 584–598 (2019).

112. Zoogy, Avances del monitoreo de Zoogoneticus tequila y Notropis amecae en el Río Teuchitlán. *zoogoneticustequila* (2021), (available at https://zoogoneticustequila.wixsite.com/zoogoneticustequila/post/avances-del-monitoreo-de-zoogoneticus-tequila-y-notropis-amecae-en-el-río-teuchitlán).

113. T. Woodfine, T. Gilbert, "The Fall and Rise of the Scimitar-Horned Oryx: A Case Study of Ex-Situ Conservation and Reintroduction in Practice" in *Antelope Conservation*, J. Bro-Jørgensen, D. P. Mallon, Eds. (John Wiley & Sons, Ltd, Chichester, UK, 2016; https://onlinelibrary.wiley.com/doi/10.1002/9781118409572.ch14), pp. 280–296.

114. R. Ogden, J. Chuven, T. Gilbert, C. Hosking, K. Gharbi, M. Craig, S. S. Al Dhaheri, H. Senn, Benefits and pitfalls of captive conservation genetic management: Evaluating diversity in scimitar-horned oryx to support reintroduction planning. *Biol. Conserv.* **241**, 108244 (2020).

115. A. Elbein, The Texotics. *Tex. Obs.* (2020), (available at https://www.texasobserver.org/the-texotics/).

116. T. Gilbert, “International studbook for the scimitar-horned oryx Oryx dammah. Seventeenth edition” (Winchester, UK, Marwell Wildlife, 2022), p. 1067.

117. T. Gilbert, thesis, University of Southampton (2011).

118. C. Lees, P. Miller, R. Beudels-Jamar, J. Newby, “Scimitar-horned Oryx Conservation Planning Workshop II: Workshop Report” (IUCN/SSC Conservation Breeding Specialist Group, Apple Valley, MN, 2010), p. 56.

119. ZSL, Two Extinct-in-the-Wild Partula snail species returned to the wild for first time in 25 years. *Zool. Soc. Lond. ZSL* (2019), (available at https://www.zsl.org/conservation/news/two-extinct-in-the-wild-partula-snail-species-returned-to-the-wild-for-first-time).

120. S. M. Haig, J. D. Ballou, N. J. Casna, Genetic Identification of Kin in Micronesian Kingfishers. *J. Hered.* **86**, 423–431 (1995).

121. A. E. Trask, G. M. Ferrie, J. Wang, S. Newland, S. Canessa, A. Moehrenschlager, M. Laut, L. B. Duenas, J. G. Ewen, Multiple life-stage inbreeding depression impacts demography and extinction risk in an extinct-in-the-wild species. *Sci. Rep.* **11** (2021), doi:10.1038/s41598-020-79979-4.

122. R. B. Walter, L. Hazlewood, S. Kazianis, *The Xiphophorus Genetic Stock Center Manual* (Texas State University, 2006).

123. XNP project annual report – year 4 | conservation.oevvoe.org, (available at https://www.conservation.oevvoe.org/en/xnp-project-annual-report-%E2%80%93-year-4).

124. J. Martínez-Gómez, "Re-Introduction of the Socorro dove, Socorro Island, Revillagigedo Archipelago, Mexico." in *Global Re-introduction Perspectives: Additional case-studies from around the globe* (IUCN/SSC Re-introduction Specialist Group, Abu Dhabi, UAE, 2010), pp. 182–186.

125. Encephalartos Relictus. *Exclus. Cycads SA*, (available at https://exclusivecycadssa.com/index.php/cycad-blog/focus-on/189-encephalartos-relictus).

126. S. Poursaeid, B. Falahatkar, Threatened fishes of the world: Stenodus leucichthys leucichthys Güldenstädt, 1772 (Salmonidae). *Aqua Int. J. Ichthyol.* **18**, 31–35 (2012).

127. Conservation of Abutilon Pitcairnense | National Botanic Gardens of Ireland, (available at https://botanicgardens.ie/2011/01/10/conservation-of-abutilon-pitcairnense/).

128. S. Godefroid, J. Piqueray, L.-M. Delescaille, A. Monty, G. Mahy, A framework to identify constraints to post-extinction recovery of plant species—Application to the case of Bromus bromoideus. *J. Nat. Conserv.* **54**, 125802 (2020).

129. [Science news] - Successful reintroduction of the brome of the Ardennes in Wallonia! *Plantentuin Meise*, (available at https://www.plantentuinmeise.be/en/nieuws/201/_Science_news_Successful_reintroduction_of_the_brome_of_the_Ardennes_in_Wallonia_).

130. USFWS, “Cyaneapinnatifida (Haha) 5-Year Review Summary and Evaluation” (2007), (available at https://ecos.fws.gov/docs/tess/species_nonpublish/1096.pdf).

131. D. J. Adamski, T. J. Chambers, M. D. E. Akamine, K. Kawelo, Reintroduction approaches and challenges for Cyanea superba (Cham.) A. Gray subsp. superba. *J. Nat. Conserv.* **57**, 125873 (2020).

132. Deppea splendens. *Calif. Acad. Sci.*, (available at https://www.calacademy.org/explore-science/deppea-splendens).

133. Governor Laffan’s Fern. *Gov. Bermuda Dep. Environ. Nat. Resour.*, (available at https://environment.bm/governor-laffans-fern).

134. Franklinia tree returns to its original south Georgia home. *AccessWDUN* (2002), (available at http://accesswdun.com/article/2002/4/195877).

135. E. Fischer, C. M. Rodriguez, 690. Nymphaea Thermarum. *Curtiss Bot. Mag.* **27**, 318–327 (2010).

136. M. Ricci, L. Eaton, Do all existing Sophora toromiro descend from one individual? *Biodivers. Conserv.* **6**, 1697–1702 (1997).

137. M. Maunder, A. Culham, B. Alden, G. Zizka, C. Orliac, W. Lobin, A. Bordeu, J. M. Ramirez, S. Glissmann-Gough, Conservation of the Toromiro Tree: Case Study in the Management of a Plant Extinct in the Wild. *Conserv. Biol.* **14**, 1341–1350 (2000).

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Supplementary Materials

Materials and Methods

Tables S1 to S5

References (93 – 137)

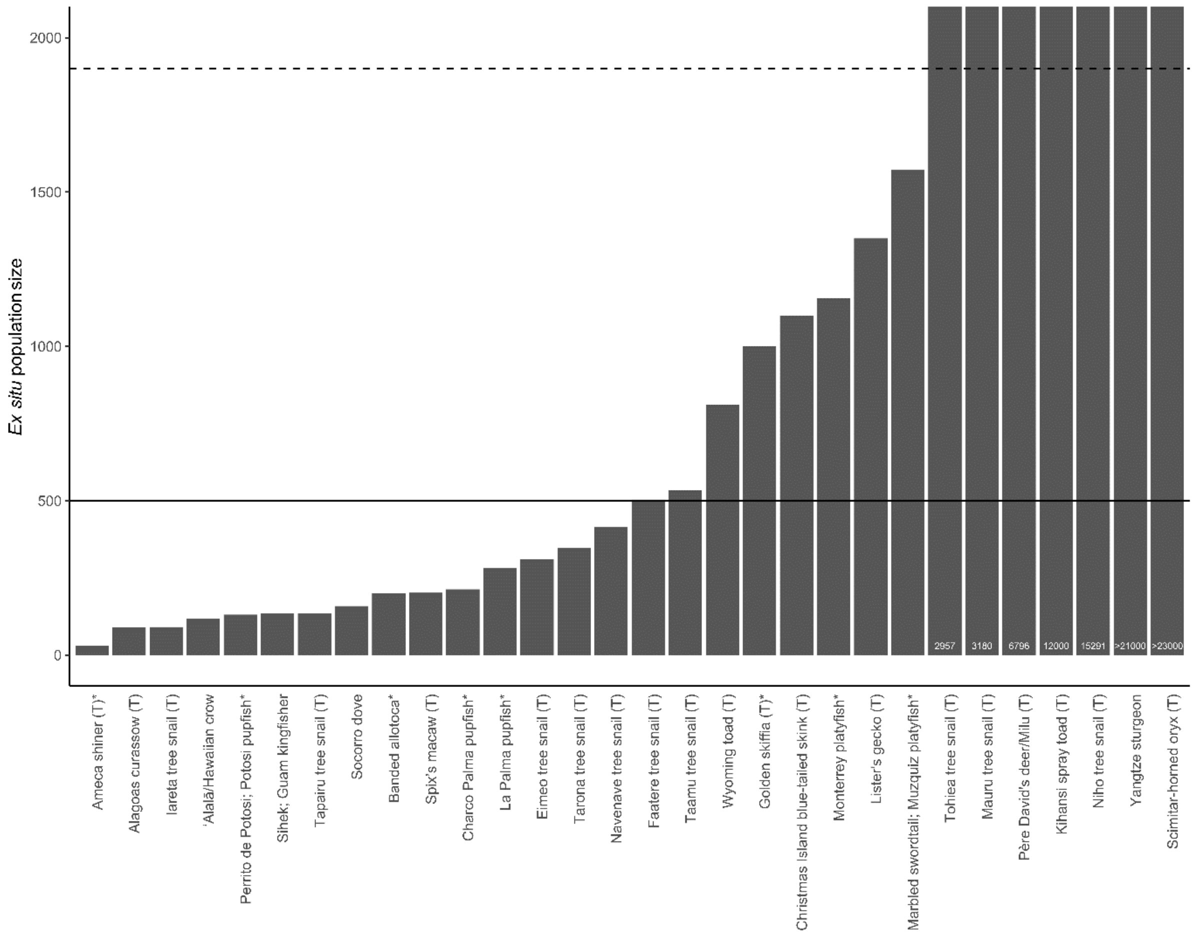

Fig. 1. Estimated *ex situ* population sizes of EW animal species. Solid horizontal line: Minimum N_e recommended to minimise loss of genetic diversity (500). Dashed horizontal line: minimum census population size expected to ensure effective population size of 500 (1900 individuals, see (*37*)). Where population sizes are above 2000, the total size is denoted at the base of the bar. Population estimates are for 30 of the 32 EW animal species held *ex situ*. They were compiled using Zoological Information Management System (ZIMS) (*22*), a database representing the real-time holdings of more than 1100 zoological and aquarium collections globally, combined with academic and grey literature, and advice from relevant taxon experts and conservation practitioners. Species marked with an asterisk (*) may have additional individuals kept by hobbyists. Species marked with (T) have additional *in situ* populations as a result of conservation translocations, but these are not yet considered wild under the Red List.

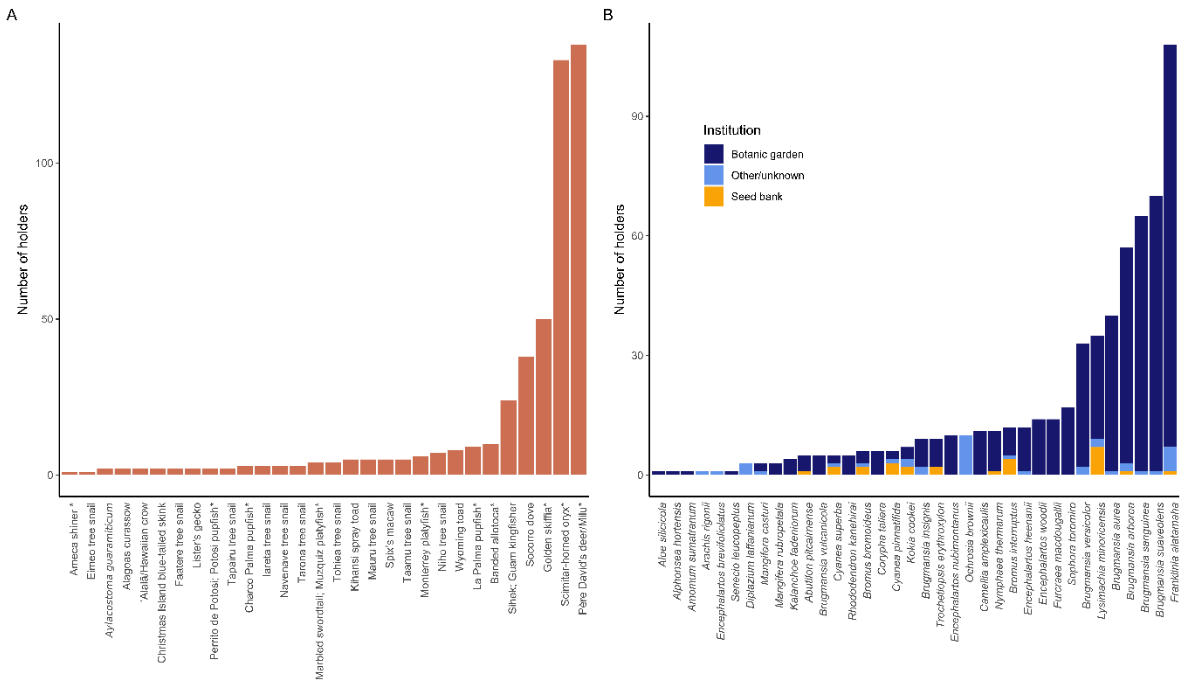

Fig. 2. Holders of *ex situ* EW species. Panel A: Estimates number of holders for 30 of the 32 EW animal species held *ex situ*. Estimates produced as for Fig. 1. Species marked with an asterisk (*) may have additional individuals kept by hobbyists. Panel B: Estimates for number and type (botanical garden, seed bank, or unknown) of *ex situ* holders of 36 of the 39 EW plant species. Compiled using PlantSearch, a database reporting the living plant, seed, and tissue holdings of more than 1100 botanical collections globally (*27*), combined with academic and grey literature, and advice from relevant taxon experts and conservation practitioners.

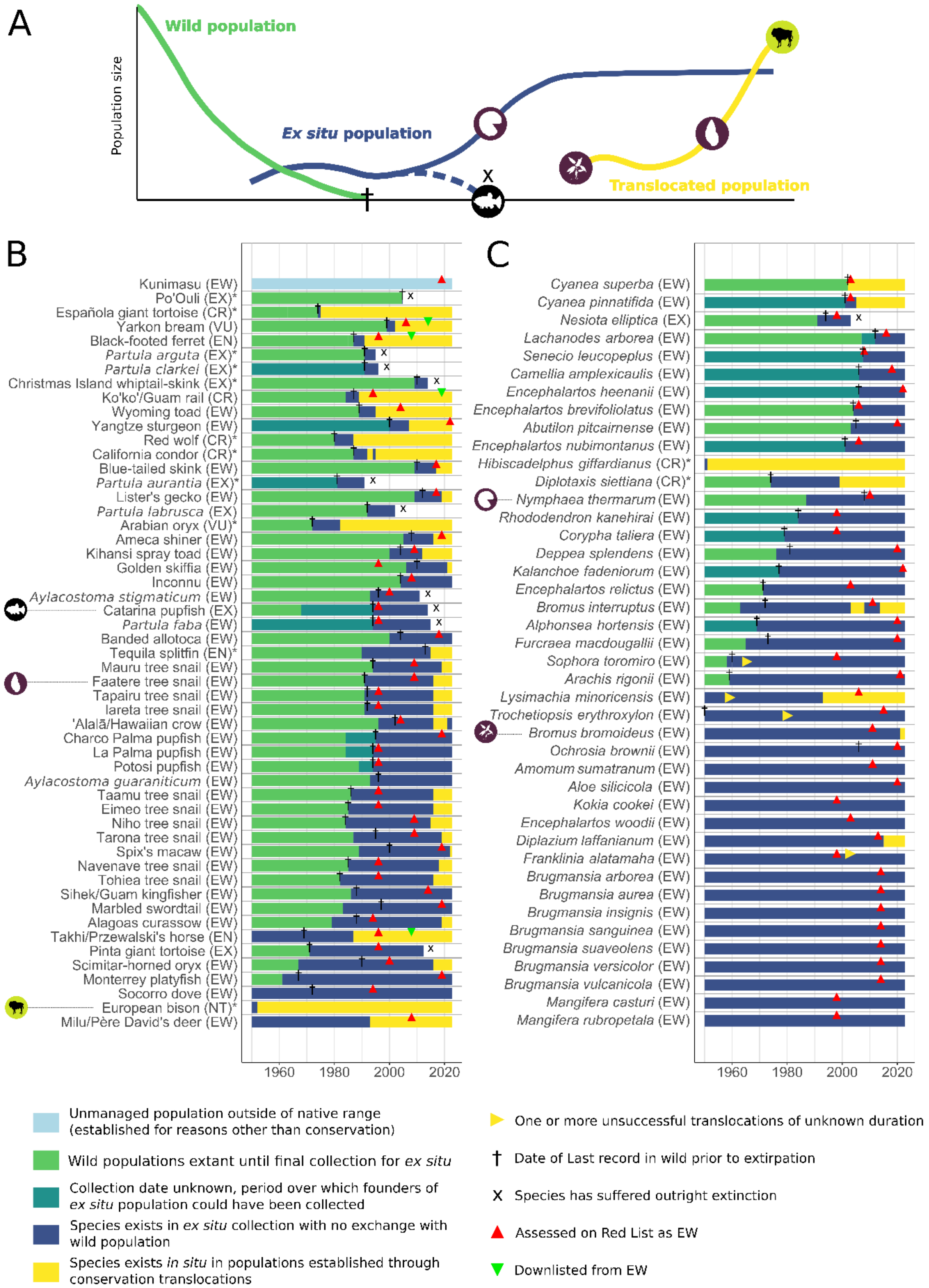

Fig. 3. The conservation history of all species known to have met the definition of EW since 1950. (A) Schematic showing stages in the process of recovery of highly threatened species through collection for *ex situ* care, *ex situ* population growth and maintenance, and return to the wild through translocations. Pathways through these stages or towards extinction are illustrated with icons representing example species in panels B and C. **(B & C)** Timelines

representing the history of this process for all animal **(B)** and plant **(C)** species that would have met the definition of EW since 1950. Colours represent the population status and activity over the time period depicted. Species are listed in ascending order of time spent in *ex situ* care experiencing no exchange with wild populations (using the minimum possible duration where this is not known with certainty). The present Red List status is listed in parentheses after the common name (animals) or scientific name (plants). Species marked with an asterisk (“*”) have never been listed as EW on the Red List.

Table 1. Species that have gone extinct after having been *ex situ*-restricted since 1950.

Scientific name	Common name	Kingdom	Class	Year last recorded in wild	Extinction year	Published Red List assessments	Notes	Additional references
Aylacostoma stigmaticum		Animals	Gastropoda	1996	2011	EW (2000).	Collected from the wild into *ex situ* care in 1993 prior to the filling of a reservoir in its native habitat. The last known wild population disappeared by 1996. This species became extinct outright in 2011 due to a disease outbreak in *ex situ* facilities whose causal agent was unidentified but was suspected to be viral.	
Chelonoidis abingdonii	Pinta giant tortoise	Animals	Reptilia	1972	2012	EX (2016); EW (1996, as *Geochelone nigra abingdoni*)	The last known individual of the species, known as Lonesome George, survived in *ex situ* care from his collection in 1972 until his death in 2012 marked the extinction of the species.	
Emoia nativitatis	Christmas Island whiptail-skink	Animals	Reptilia	2010	2014	EX (2017); CR (2010).	Declines in wild first reported 1998, likely driven by introduced species. Three females caught in 2009 in an attempt to start captive breeding. Last known individual of species died *ex situ* in 2014.	(*13*)
Melamprosops phaeosoma	Po'Ouli	Animals	Aves	2004	2004	EX (2019); CR (1994, 1996, 2000, 2004, 2007, 2008, 2009, 2012, 2013, 2016, 2018); T (1988).	By 1997, only three individuals were known. The last sightings for two of these were in December 2003 and January 2004. The last known individual was captured in September 2004, but died in captivity 78 days later in November 2004.	(*72*)
Megupsilon aporus	Catarina pupfish	Animals	Actinopterygii	1994	2014	EX (2019); EW (1996); E (1994, 1990, 1988, 1986).	Was endemic to Potosi Spring, which dried out due to groundwater extraction. The species was difficult to maintain in captivity, being sensitive to environmental conditions and vulnerable to infections. Serious declines occurred in 2013, and its scattered distribution across multiple holders likely inhibited full appreciation of the significance of these. The last remaining individual died in 2014.	(*57*)
Nesiota elliptica	St Helena olive	Plants	Magnoliopsida	1994	2003	EX (2016, 2004); EW (2003, 1998).	This species, native to Saint Helena, was rediscovered in the remnants of its native habitat in 1977. This last known wild individual died in 1994, but seeds and cuttings taken from the tree led to attempts to cultivate	(*73*)

							the species *ex situ*. It proved difficult to maintain, and fungal infections killed the final seedlings and cuttings in 2003.	
Partula arguta		Animals	Gastropoda	1991	1995	EX (1996, 2009); EN (1994).	Endemic to Huahine, Society Islands. As is the case for the other *Partula* species covered by this study, this species was collected into *ex situ* care prior to extirpation from the wild due to the introduction of the carnivorous snail *Euglandina rosea*. Last known individual died *ex situ* in 1995.	(*42*, *74*, *75*)
Partula aurantia	Moorean viviparous tree snail	Animals	Gastropoda	1981	1991	EX (2019, 2009, 2006); EN (1994).	Endemic to Moorea, Society Islands. As is the case for the other *Partula* species covered by this study, this species was collected into *ex situ* care prior to extirpation from the wild due to the introduction of the carnivorous snail *Euglandina rosea*. The last individual died in *ex situ* care in 1991	(*76*–*78*)
Partula clarkei (Reclassified from *P. turgida*)		Animals	Gastropoda	1991	1996	EX (1994, 1996, 2009).	Endemic to Raiatea, Society Islands. As is the case for the other *Partula* species covered by this study, this species was collected into ex situ care prior to extirpation from the wild due to the introduction of the carnivorous snail *Euglandina rosea*. Last known individual died *ex situ* in 1996 after abrupt population declines attributed to microsporidian parasites (*70*), but the causal agent has since been questioned (*14*).	(*42*, *79*)
Partula faba		Animals	Gastropoda	1994	2015	EW (2009, 1996); E (1994).	Endemic to Raiatea and Tahaa, Society Islands. As is the case for the other *Partula* species covered by this study, this species was collected into *ex situ* care prior to extirpation from the wild due to the introduction of the carnivorous snail *Euglandina rosea*. The last individual died in *ex situ* care in 2015.	(*42*)
Partula labrusca		Animals	Gastropoda	1992	2002	EX (2009); EW (1996); E (1994).	Endemic to Raiatea, Society Islands. As is the case for the other *Partula* species covered by this study, this species was collected into ex situ care prior to extirpation from the wild due to the introduction of the carnivorous snail *Euglandina rosea*. The last individual died in *ex situ* care in 2002.	(*42*)

Not all species were listed on the Red List as EW, see "published Red List assessments" column for details. Key to Red List categories: CR: Critically Endangered; E: Endangered (pre-1994 category); EN: Endangered; EX: Extinct; EW: Extinct in the Wild; NT: Near Threatened; T: Threatened (pre-1994 category); VU: Vulnerable

Table 2. Species that have regained IUCN wild status after having been *ex situ*-restricted since 1950.

Scientific name	Common name	Kingdom	Class	Last reported in wild	Number of individuals collected (of which, number of founders)	Year conservation translocations started (R: Reintroduction, AC: Assisted Colonization)	Published Red List assessments	Notes	Additional references
Acanthobrama telavivensis	Yarkon bream	Animals	Actinopterygii	1999	150	R: 2002	VU (2014); EW (2006).	Native to coastal streams of Israel, this species declined across the second half of the twentieth century until a severe drought in 1999 dried out the last remnants of its habitat. To secure the future of the species, 150 fish were brought into *ex situ* care in the days prior to extirpation. Reintroduction attempts followed just three years later which were further refined in subsequent years alongside habitat restoration. The species now has a growing population in the wild again.	(*80*)
Bison bonasus	European bison	Animals	Mammalia	1927	54 (12)	R: 1952	NT (2020); VU (2008); EN (2000, 1996); V (1994, 1990, 1988); "Very rare but believed to be stable or increasing" as *B. b. bonasus* (1965)	Once distributed across western, central, and south-eastern Europe. Declined alongside human expansion with its associated hunting pressure and ecosystem alteration. Finally extirpated from the wild in 1927, but survived in European zoos. A breeding project commenced in Białowieża, Poland, in 1929, leading to the first reintroductions back into the wild in 1952. Wild populations have grown to the point of the current categorisation of Near Threatened, though the species still depends on conservation management.	(*81*, *82*)
Canis rufus	Red wolf	Animals	Mammalia	1980	14 (12)	R:1987	CR (2018, 2004, 1996); E (1994, 1990, 1988, 1986, 1982)	Once common in the eastern United States, the red wolf declined due to human persecution and hybyidisation with coyotes (*Canis latrans*). 400 canids were collected from the wild between 1973 and 1980, from which what were believed to be the last fourteen pure red wolves were selected to initiate an *ex situ* population.	(*83*)
Chelonoidis hoodensis	Española giant tortoise	Animals	Reptilia	1974	15 (15)	R: 1975 AC: 2015	CR (2017, 2016, 1994 as *Geochelone*	Endemic to Española, the Galápagos Islands, exploitation for human consumption and habitat degradation drove the wild population to a low	(*84*, *85*)

							nigra hoodensis)	point of 14 in 1974, at which point all remaining individuals were removed to establish an *ex situ* population (joined by an additional male already present in San Diego Zoo). Reintroductions commenced the following year. Used as an ecological replacement for a now-extinct tortoise species on Santa Fe island from 2015.	
Diplotaxis siettiana	Jaramago de Alborán	Plants	Magnoliopsida	1974	Not reported	R: 1999	CR (2011, 2006); EX (1998)	Endemic to the island of Alborán, Spain. Extensive human modification of habitat, particularly the introduction of cattle, likely led to declines. Species was not seen after 1974. Reintroductions commencing in 1999 established a self-sustaining population.	(*11*)
Equus ferus	Takhi; Przewalski's Horse	Animals	Mammalia	1969	53 (12)	R: 1997	EN (2015, 2011); CR (2008); EW (1996).	Ranged across the Eurasian steppe from Russia east to northern China and Mongolia until the 1800s, around which point it began to decline. Remnant populations persisted until the last wild individual was recorded in the Dzungarian Gobi Desert in 1969. 11 of 12 founders contributing to present population had been captured into *ex situ* care between 1899 and 1902, with 1 additional mare caught in 1947. Reintroductions commenced in Mongolia in the 1990s.	(*86*)
Gymnogyps californianus	California condor	Animals	Aves	1987	22 (14)	R: 1992 & 1994	CR (2020, 2018, 2017, 2016, 2015, 2013, 2012, 2010, 2009, 2008, 2006, 2004, 2000, 1996, 1994); T (1988).	Precipitous population declines in the twentieth century driven largely by persecution and poisoning due to consumption of carcasses containing lead shot. The last known individuals of the species were collected from the wild by 1987 to initiate an *ex situ* population. Reintroductions started 1992. All reintroduced individuals were collected back into captivity in 1994 due to behavioural problems. Reintroductions recommenced 1995.	(*87*)
Hibiscadelphus giffardianus		Plants	Magnoliopsida	1930	1	R: 1951	CR (1998); E (1978)	Only one individual of this small tree native to Hawai'i was ever known. This tree died in 1930, but seeds were collected and the species was propagated *ex situ*. Replanted in original habitat between 1951 and 1964.	(*88*)
Hypotaenidia owstoni	Ko'ko'; Guam Rail	Animals	Aves	1987	22	AC: 1989 R: 1998	CR (2019); EW (2016); EW (2012, 2010, 2008, 2004, 2000, 1996, 1994, as	Extirpation from Guam in 1987 driven largely by brown tree snakes. Conservation translocations started on the island of Rota (outside of native range) in 1989, but, despite evidence of breeding here, this population is not considered to be self-sustaining due to the continued release efforts	(*89*, *90*)

							Gallirallus owstoni); T (1988, as *Rallus owstoni*).	required to ensure its persistence. A 1998 release into a snake-controlled area in Guam failed due to destruction of the snake barrier by a typhoon in 2002. Releases on the island of Cocos starting in 2010 have seen breeding (by 2014), and this population is now considered self-sustaining and was the basis for downlisting to CR in 2019.	
Oryx leucoryx	Arabian oryx	Animals	Mammalia	1972	≥17 (17)	R: 1982	VU (2017, 2011); EN (2008,2003, 1996); E (1994, 1990, 1988, 1986); "Very rare and believed to be decreasing in numbers" (1965).	Once distributed across the Arabian Peninsula, experienced steep population declines in the twentieth century. Last reported in the wild in 1972. A captive program was commenced in 1962-63 in the USA with nine individuals, at least three of which were wild caught for conservation purposes. In parallel to this, a collection was established in Riyadh containing additional animals from Saudi Arabia and Qatar, as well as individuals from the USA herd. In 1993, the global population was reported to be derived from 17 wild-caught founders.	(*91*)
Mustela nigripes	Black-footed Ferret	Animals	Mammalia	1987	18 (7)	R: 1991	EN (2015, 2008); EW (1996); E (1994, 1990, 1988, 1986, 1982); "Very rare and believed to be decreasing in numbers" (1965)	The black-footed ferret was once distributed across west central North America, from southern Canada to northern Mexico, tightly linked to the habitat of its principal prey, prairie dogs (*Cynomys* spp.). Habitat conversion, persecution of prairie dogs as an agricultural pest, and sylvatic plague led to precipitous ferret declines across the twentieth century. The species was thought lost in the 1970s until discovery of a declining small population in 1981. The last known individuals were captured into *ex situ* care in 1987. Multiple reintroductions starting in 1991 have resulted in at least three self-sustaining wild populations.	(*92*)
Zoogoneticus tequila	Tequila splitfin	Animals	Actinopterygii	2013	6	R: 2015	EN (2019); CR (2009)	Endemic to the upper Río Ameca in Jalisco, Mexico. Extirpated in 2013, probably due to the impacts of introduced species and habitat degredation. Reintroductions started in 2015, establishing a population that is currently growing.	

Not all species were listed on the Red List as EW, see "published Red List assessments" column for details. Key to Red List categories: CR: Critically Endangered; E: Endangered (pre-1994 category); EN: Endangered; EX: Extinct; EW: Extinct in the Wild; NT: Near Threatened; T: Threatened (pre-1994 category); VU: Vulnerable

Table 3. Number of individuals initiating *ex situ* populations, and—where reported—number of founder lineages currently represented, of animal (left) and plant (right) EW species.

Animal species	Number of individuals collected (of which, number of founders)	Plant species	Number of individuals collected
Alagoas curassow	5 (3)	*Abutilon pitcairnense*	1
Ameca shiner	6	*Cyanea pinnatifida*	1
Wyoming toad	10	*Encephalartos relictus*	1
ʻAlalā (or Hawaiian crow)	10 (9)	*Encephalartos woodii*	1
Spix's macaw	17 (7)	*Kokia cookei*	1
Socorro dove	17	*Sophora toromiro*	1
Milu (or Père David's deer)	18 (11)	*Cyanea superba*	3

Sihek (or Guam kingfisher)	29 (16)	*Diplazium laffanianum*	5
Lister's gecko	43		
Golden skiffia	<50		
Scimitar-horned oryx	48-60		
Blue-tailed skink	66		
Kihansi spray toad	499		

Supplementary materials

Materials and Methods

We compiled a list of all species historically qualifying for the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Red List) category of Extinct in the Wild (EW) (*4*). The EW category is applied to any species "known only to survive in cultivation, in captivity or as a naturalized population (or populations) well outside the past range" (*12*). We will hereafter refer to species that we regard as having met one of the first two conditions as having been *ex situ*-restricted and reserve the term EW for those species that have been officially assessed on the Red List as such. We are aware of only one species, the kunimasu (*Oncorhynchus kawamurae*), that has been assessed as EW on the basis of being restricted to naturalized populations outside of its native range established through intentional release for commercial fishing purposes (*93*). This essentially wild state is not the primary focus of this study.

Though the EW category was first introduced by the IUCN in 1994 (*19*), we extended our analysis back to 1950, approximating the start of modern species conservation (*20*). This time window enabled us to build a comprehensive list of species in a comparable context, minimising the risk of biasing our selection towards well-known cases. Some species that were historically *ex situ*-restricted, such as the thylacine (*Thylacinus cynocephalus*) or passenger pigeon (*Ectopistes migratorius*), therefore fell outside of our scope.

The assessments of the 84 species (40 animals and 44 plants) currently categorised as EW were extracted from the Red List version 2022-2 (*4*). Species that were formerly EW but have since been assessed as extinct (three animal species, and one plant species Table 1) or have been downlisted to another category (i.e., an improvement in conservation status: four animal species, Table 2) were compiled from IUCN summary statistics for "genuine" status changes (*4*). Genuine Red List changes are reassignments in category as a result of true improvements or deteriorations in the species' status, as opposed to revisions based on previously-unavailable information, taxonomic revision, correction of error, or an update in the criteria version used. We then identified additional species that would have been *ex situ*-restricted at any point between 1950 and the introduction of the EW category in 1994. Such a historical state is not currently recorded in any systematic way in the Red List, but the information is often contained within the narrative text of assessments. Therefore, to find cases of such species that have since gone extinct, we reviewed the narrative texts of the Red List assessments of all 180 extinct species with a "year last seen" reported as 1950 or later for descriptions of an *ex situ*-restricted state. It was not feasible to similarly manually review every assessment of an extant species, given that their number exceeds 140000. However, if any such species had once been *ex situ*-restricted, its populations that are now considered wild must have been established via a conservation translocation. We therefore reviewed the Red List assessments of all species that have distributions whose origins are coded as "reintroduced" or "assisted colonisation". In case of incomplete or incorrect origin coding, we also searched the narrative text of all Red List assessments for the phrase "extinct in the wild" for mention of species that are acknowledged as having previously occupied the state without having been assessed as such.

Through these approaches, we identified 13 additional species (11 animals and two plants) that were at some point *ex situ*-restricted but never recorded on the Red List as EW (see Table 1 for the five species that have since gone extinct, and Table 2 for the eight species that have since returned to the wild). We also identified an additional plant species that is now extinct having previously been assessed as EW but was not included in IUCN summary statistics on genuine status changes (see Table 1).

Confirmation of outright extinction in the wild is an exhaustive process (*53*) beyond the scope of this study. We therefore refrained from searching for species whose purported recent extinction in the wild has not yet been confirmed in their Red List assessments. Similarly, while we have collated information on attempts to re-establish EW species into the wild, we have refrained from engaging in any consideration as to whether these *in situ* populations should be considered to have reached wild status, thus prompting a downlist of the species. We again defer to the Red List process to make such determinations. We considered any reported extinction in *ex situ* care of a species already assessed as EW to be unambiguous, however, and incorporated these where relevant (two species, see Table 1). We identified a further ten species (five animals and five plants) currently assessed as EW whose assessments appear erroneous: two are extinct having never been in *ex situ* care, three are likely extant in the wild having never been extirpated, three are synonyms of species that remain extant in the wild, and the statuses of two are unknown (Table S1).

We therefore report on 95 species (52 animals and 43 plants) that are known to have been extirpated to *ex situ* care since 1950, 72 of which (33 animals and 39 plants) are considered to remain in this state as of 2022. For each species, we collected information on the history of the collection, *ex situ* maintenance, and conservation of each, namely: the periods over which founders of the *ex situ* population were collected from the wild; the number of individuals collected to initiate the *ex situ* population; the number of founders represented in the present population (where this is noted as a separate number); the year the species was last recorded in the wild; and the timing and status of any attempts to re-establish the species in the wild through conservation translocations. Following IUCN guidelines for reintroductions and other conservation translocations (*66*), we considered conservation translocations as involving the intentional release of individuals into the wild for the purpose of the conservation of the species. Releases into indigenous range were counted as reintroduction attempts, and those outside of indigenous range were counted as assisted colonisations (*66*). Where this information was not contained in a Red List assessment, we sought it from recovery project documentation and academic literature. Where information appeared incomplete or unclear, we contacted taxon experts and conservation practitioners identified through the literature, studbook listings on ZIMS, and through the relevant IUCN taxonomic specialist group. We additionally ran targeted Google and Google News searches using the common and scientific names of each species and reviewed the first 30 results, as information on actions such as recent conservation translocations is often captured on project websites and news reports but not in the scientific or grey literature. Where information was obtained from sources outside the Red List, it is indicated in the "additional references" column in Tables 1, 2, and S1-S4.

The status of the *ex situ* populations of currently EW species was assessed by quantifying the number of institutions holding them; the type of institution for plants (i.e., botanical garden or seed bank); the total *ex situ* population size for animals (this is not generally quantified or reported for plants); whether an animal species was subject to metapopulation management or had a studbook; and whether any Population Viability Analyses (PVAs) had been carried out for *ex situ* populations. Information on studbooks, the number of holders, and population sizes for animal species was obtained on January 3rd 2023 from the Zoological Information Management

System (ZIMS), a database representing the real-time holdings of more than 1100 zoological and aquarium collections globally, maintained by the conservation and wildlife care NGO Species360 (*22*). We recorded whether a species was part of a cooperative breeding program by consulting the Association of Zoos and Aquariums' database of Species Survival Programs (SSPs) (*23*), the European Association of Zoos and Aquaria's list of EEPs (*24*), Australasia's Zoo Aquarium Association's list of Species Management Programs (SMPs) (*25*), and the World Association of Zoos and Aquariums' list of Global Species Management Plans (*26*). Information for plant species was obtained from PlantSearch, a database reporting the living plant, seed, and tissue holdings of more than 1100 botanical collections globally, maintained by Botanic Gardens Conservation International (*27*). PlantSearch receives disaggregated collections data from individual gardens and also differentiates between seed bank and living plant collections. From this disaggregated data it is possible to calculate the number of different institutions that hold collections of any given taxon. However, it is not possible to assess whether these collections are of different provenances, meaning that PlantSearch data gives only a rough indication of the breadth of genetic diversity held *ex situ*. PlantSearch does not record population sizes; these are maintained on individual gardens' collection management databases, most of which were not available to this study. This situation is about to change with the development of a plant exchange pedigree tool, based on the zoo model, and due to be launched in 2023 (*30*, *43*). To assess the usage of PVAs in the *ex situ* management of EW species, we ran Google searches for the species and common name combined with the terms "population viability analysis" and "PVA" and reviewed the first 30 results where present.

Through our review of the literature and other material described above, and by contacting individual institutions and taxon experts, we were able to incorporate additional information on EW species. *Ex situ* EW populations external to the ZIMS and PlantSearch databases were collated for seventeen species (thirteen animals and four plants) eight of which (four animals and four plants) were not otherwise represented. We were unable to obtain detailed information on the *ex situ* populations of three EW species (one animal and two plants, see Table S3 for details). Through this approach we have collated the most comprehensive and relevant overview of the *ex situ* populations of EW species feasible (Figs 1-2, Tables S2-S4). However, we acknowledge that there will be some material outside of the reach of our survey, such as that maintained by hobbyists and private collectors. We note, for example, that this is likely the case for eight Mexican freshwater fish species (see Fig. 1). Additionally, many institutions do not update their PlantSearch records regularly, so shifts in holdings may have occurred since species were last accessioned. However, we do not expect that any such alterations would significantly alter our population summaries.

To predict the seed storage behaviour of EW plant species, we applied the model developed by Wyse and Dickie and available through the web interface presented at https://seedcollections.shinyapps.io/seed_storage_predictor/ (*47*). This model harnesses an extensive dataset to predict the probability that a given species will produce desiccation-sensitive (recalcitrant) seeds. This prediction is based on: published seed storage information, taxonomic relationships between the species in question and species with known seed storage behaviour, climate and elevation data for the species, woodiness, seed mass, and dispersal mode. The model is run at three different taxonomic levels—order, family, or genus—depending on the degree of information available, with predictions based on higher taxonomic levels giving less reliable results. Results based on species level are not model predictions, being instead directly based on existing information in the database for that species. The model returns a probability of a species being recalcitrant between 0 (desiccation-tolerant (orthodox)) and 1 (recalcitrant). Results closer to 0.5 are less reliable. We were unable to obtain a prediction for four species: *Diplazium laffanianum*, *Encephalartos heenanii*, *Encephalartos relictus*, *Kalanchoe fadeniorum.* 31 of the remaining 35 species were predicted (27 species) or known (four species) to have orthodox seed storage behaviour, the remaining four species were predicted to have recalcitrant seeds. Predictions were mostly based on family (18 species) or genus (10 species). See Table S5 for detailed model output. These predictions give an indication of the extent of seed desiccation tolerance in our dataset, but we emphasise that experimentation and improved reporting of seed storage behaviour in EW plant species is a critical need.

Table S1.

Scientific name	Kingdom	Class	Proposed true status	Justification	Additional references
Agave lurida	Plants	Liliopsida	Synonym	Synonym of *Agave vera-cruz*, which is not yet assessed on the Red List but is extant in the wild in its native Mexico as well as introduced populations in South America and Asia.	(*94*, *95*)
Aylacostoma chloroticum	Animals	Gastropoda	Extant in wild	Believed to be extirpated from the wild by 1996, but additional populations were discovered in 1997 and 2003. One population remains, though it is threatened by high parasitic worm burden.	
Cyrtandra waiolani	Plants	Magnoliopsida	Unknown	No indication of *ex situ* material in 2003 Red List EW assessment. 2019 US Fish and Wildlife review confirms the absence of *ex situ* material and suggests the possibility of rediscovery in the wild.	(*96*)
Dombeya rodriguesiana	Plants	Magnoliopsida	Extant in wild	Following IUCN Red List Categories and Criteria version 3.1 (*11*), we consider a species to be EW only when exhaustive surveys have failed to find an individual in the wild. As the last wild individual of this species remains *in situ*, we don't yet consider this species EW.	(*12*, *97*)
Euphorbia mayurnathanii	Plants	Magnoliopsida	Synonym	Synonym of *Euphorbia antiquorum*, which is assessed as Least Concern.	(*94*)
Erythroxylum echinodendron	Plants	Magnoliopsida	Synonym	Synonym of *Erythroxylum minutifolium*, which is extant in the wild in Cuba	(*94*, *98*)
Leptogryllus deceptor	Animals	Insecta	Unknown	No record of having been kept *ex situ*, or indeed having been seen or collected beyond its original description in 1910.	
Partula dentifera	Animals	Gastropoda	Extinct	This species was driven to extinction as a result of the introduction of the predatory snail *Euglandia rosea* to the Society Islands in the late 1980s. Individuals of *Partula navigatoria* in the *ex situ* program were initially misidentified as this species, and the taxon was consequently erroneously assessed as EW.	(*42*)
Partula tristis	Animals	Gastropoda	Extinct	This species was driven to extinction as a result of the introduction of the predatory snail *Euglandia rosea* to the Society Islands in the late 1980s. Individuals of *Partula garrettii* in the *ex situ* program were initially misidentified as this species, and the taxon was consequently erroneously assessed as EW.	(*42*)
Thermosphaeroma thermophilum	Animals	Malacostraca	Extant in wild	This species was almost extirpated when its native spring dried out in 1988. Flow was restored the following month, flushing out some individuals that had persisted in the plumbing adjoining the spring. The wild population was therefore never fully extirpated, and the species never truly EW.	(*99*)

Species currently assessed (Red List 2022-2) as EW regarded in this study as erroneous.

Table S2.

Scientific name	Common name(s)	Class	Last record from wild	Collection period	Number of individuals collected (of which, number of founders represented)	*Ex situ* population size	Number of *ex situ* holders	Population management	Year conservation translocations started (R: Reintroduction, AC: Assisted Colonization)	Additional references
Acipenser dabryanus	Yangtze sturgeon	Actinopterygii	2000	After 1980	Not reported	Over 21000 first- and second-generation mature fish. Breeding capacity over one million.	Not reported		R: 2007	(*100*)
*Allotoca goslinei**	Banded allotoca	Actinopterygii	2004	2000	Not reported	200	<10	EEP, studbook		
Anaxyrus baxteri	Wyoming toad	Amphibia	1989	1989	10	811	8	SSP, studbook	R: 1995	(*101*)
Aylacostoma stigmaticum		Gastropoda	1996	1993	Not reported	Unknown	2			
Corvus hawaiiensis	ʻAlalā; Hawaiian crow	Aves	2002	1970-1996	(9)	118	2	Studbook	R: 2016 (recaptured 2020)	(*102*, *103*)
Cryptoblepharus egeriae	Blue-tailed skink	Reptilia	2010	2009	66	1100	2	PVAs used to guide harvesting for translocations	R: 2017 AC: 2019	(*13*, *68*, *104*)
Cyanopsitta spixii	Spix's macaw	Aves	2000	1976	17 (7)	202	5	Studbook	R: 2022	(*105*)
*Cyprinodon alvarezi**	Perrito de Potosi; Potosi pupfish	Actinopterygii	1994	1989	Not reported	131	2	EEP		(*106*)
*Cyprinodon longidorsalis**	La Palma pupfish	Actinopterygii	1994	After 1984 (discovery) and before 1994 (extirpation)	Not reported	282	9	EEP		
*Cyprinodon veronicae**	Charco Palma pupfish	Actinopterygii	1995	After 1984 (discovery) and before 1995 (extirpation)	Not reported	213	3	EEP		
Elaphurus davidianus	Milu; Père David's deer	Mammalia	1868	Unknown	18 (11)	6796	138	SSP, studbook	R: 1993	(*58*, *107*)
Lepidodactylus listeri	Lister's gecko	Reptilia	2012	2009	43	1350	2	Studbook. PVAs used to guide harvesting for translocations	R: 2019	(*13*, *104*)

Mitu mitu	Alagoas curassow	Aves	1988	1979	5 (3)	90	2	Studbook	R: 2019	(*108*, *109*)
Nectophrynoides asperginis	Kihansi spray toad	Amphibia	2004	2000	499	12000	5		R: 2012	(*110*, *111*)
*Notropis amecae**	Ameca shiner	Actinopterygii	2008	2005	6	30	1		R: 2016	(*112*)
Oryx dammah	Scimitar-horned Oryx	Mammalia	Late 1980s, early 1990s	1937 - 1967	48-60	Approximately 23000	>133	SSP, EEP, SMP, studbook. PVAs previously conducted, but not used to manage global population.	R: 2016 (Considered here as first attempt to establish a wild population. However, releases into semi-wild contexts have taken place since 1985.)	(*113*–*118*)
Partula garretti	Iareta tree snail	Gastropoda	1992	1991	Not reported	91	3	EEP, studbook.	R: 2016	(*42*, *70*)
Partula hebe	Tapairu tree snail	Gastropoda	1992	1991	Not reported	135	2	EEP, studbook.	R: 2016	(*42*, *70*)
Partula mirabilis	Navenave tree snail	Gastropoda	1985	1984 - 1985	Not reported	414	3	EEP, studbook.	R: 2018	(*42*, *70*)
Partula mooreana	Eimeo tree snail	Gastropoda	1985	1985	Not reported	310	1	EEP, studbook.	R: 2016	(*42*, *70*, *76*)
Partula navigatoria	Faatere tree snail	Gastropoda	1991	1991	Not reported	504	2	EEP, studbook.	R: 2016	(*42*, *70*)
Partula nodosa	Niho tree snail	Gastropoda	1984	1984	Not reported	15291	7	EEP, studbook.	R: 2015	(*42*, *76*)
Partula rosea	Tarona tree snail	Gastropoda	1987	1987	Not reported	348	3	EEP, studbook.	R: 2019	(*42*, *119*)
Partula suturalis	Taamu tree snail	Gastropoda	1986	1980 - 1986	Not reported	533	5	EEP, studbook.	R: 2016	(*42*, *70*)
Partula tohiveana	Tohiea tree snail	Gastropoda	1982	1982	Not reported	2957	4	EEP, studbook.	R: 2016	(*42*, *70*, *76*)
Partula varia	Mauru tree snail	Gastropoda	1994	1991 - 1994	Not reported	3180	5	EEP, studbook.	R: 2019	(*42*, *119*)
*Skiffia francesae**	Golden skiffia	Actinopterygii	2010	1976 - 2006	<50	>1000	>50	EEP	R: 2021	
Todiramphus cinnamominus	Sihek; Guam kingfisher	Aves	1988	1984 - 1986	29 (16)	135	24	SSP, studbook. PVAs used to inform management.		(*120*, *121*)
*Xiphophorus couchianus**	Monterrey platyfish	Actinopterygii	1967	1961	Not reported	1157	6	Studbook		(*122*)
*Xiphophorus meyeri**	Marbled swordtail; Muzquiz platyfish	Actinopterygii	1997	1983	Not reported	1573	4	Studbook		(*122*, *123*)
Zenaida graysoni	Socorro dove	Aves	1972	1925	17	159	38	EEP, studbook		(*14*, *124*)

The collection history and present status of EW animal species held *ex situ*. Scientific names marked with an asterisk ("*") denote species for which we expect hobbyists and private collectors to hold additional individuals.

Table S3.

Scientific name	**Common name**	**Kingdom**	**Class**	**Notes**	**Additional references**
Deppea splendens		Plants	Magnoliopsida	Known from at least three *ex situ* collections, but suspected to be more widely distributed. Red List assessment indicates need for greater understanding of *ex situ* populations.	
Encephalartos relictus		Plants	Cycadopsida	The only known wild individual, a male, was collected in 1971 and relocated to the discoverer's farm. Two stems from this plant and material grown from these remain in private collections.	(*125*)
Lachanodes arborea		Plants	Magnoliopsida	Collected just prior to extirpation in the wild in 2012. Survives in cultivation in several plantations on its native Saint Helena, South Atlantic.	
Stenodus leucichthys	Inconnu	Animals	Actinopterygii	Construction of dams led to the loss of spawning grounds in the Volga, Ural, and Terek rivers. Species survives through artificial propagation, with any individuals in native range derived from releases from hatcheries, which we don't consider here to be reintroductions. No wild individuals or progeny of released individuals or are thought to exist.	(*126*)

EW Species whose *ex situ* population information is not reported in this study.

Table S4.

Scientific name	**Class**	**Last record from wild**	**Collection period**	**Number of individuals collected**	**Number of *ex situ* holders**	**Year reintroductions started (no known attempted assisted colonizations for plants)**	**Additional references**
Abutilon pitcairnense	Magnoliopsida	2005	2003	1	5		(*127*)
Aloe silicicola	Liliopsida	1920	1920	Not reported	1		
Alphonsea hortensis	Magnoliopsida	1969	Not reported	Not reported	1		

Amomum sumatranum	Liliopsida	1921	Not reported	Not reported	1		
Arachis rigonii	Magnoliopsida	1959	1959	Not reported	1		
Bromus bromoideus	Liliopsida	1935	Not reported	Not reported	6	2022	(*128, 129*)
Bromus interruptus	Liliopsida	1972	Not reported	Not reported	12	2003, 2013	
Brugmansia arborea	Magnoliopsida	Never recorded in the wild	Not reported	Not reported	57		
Brugmansia aurea	Magnoliopsida	Never recorded in the wild	Not reported	Not reported	40		
Brugmansia insignis	Magnoliopsida	Never recorded in the wild	Not reported	Not reported	9		
Brugmansia sanguinea	Magnoliopsida	Never recorded in the wild	Not reported	Not reported	65		
Brugmansia suaveolens	Magnoliopsida	Never recorded in the wild	Not reported	Not reported	70		
Brugmansia versicolor	Magnoliopsida	Never recorded in the wild	Not reported	Not reported	33		
Brugmansia vulcanicola	Magnoliopsida	Never recorded in the wild	Not reported	Not reported	5		
Camellia amplexicaulis	Magnoliopsida	Unknown	Not reported	Not reported	11		
Corypha taliera	Liliopsida	1979	Not reported	Not reported	6		
Cyanea pinnatifida	Magnoliopsida	2001	Not reported	1	6	2005	(*130*)
Cyanea superba	Magnoliopsida	Around 2000	Not reported	3	5	1998	(*131*)
Deppea splendens	Magnoliopsida	1981	1976	Not reported	Unknown		(*132*)

Diplazium laffanianum	Polypodiopsida	1905	Not reported	5	3	2014	(*133*)
Encephalartos brevifoliolatus	Cycadopsida	2004	Not reported	Not reported	1		
Encephalartos heenanii	Cycadopsida	2006	Not reported		12		
Encephalartos nubimontanus	Cycadopsida	2001	Not reported	Not reported	10		
Encephalartos relictus	Cycadopsida	1971	1971	1	Unknown		(*125*)
Encephalartos woodii	Cycadopsida	1916	Not reported	1	14		
Franklinia alatamaha	Magnoliopsida	1803	Not reported	Not reported	108	2002	(*134*)
Furcraea macdougallii	Liliopsida	1973	1953-1965	Not reported	14		
Kalanchoe fadeniorum	Magnoliopsida	1977	Not reported		4		
Kokia cookei	Magnoliopsida	1918	1915	1	7		
Lachanodes arborea	Magnoliopsida	2012	Not reported	Not reported	Unknown		
Lysimachia minoricensis	Magnoliopsida	1926	1926	Not reported	35	1959, 1993	
Mangifera casturi	Magnoliopsida	Pre-1986	Not reported	Not reported	3		
Mangifera rubropetala	Magnoliopsida	Never recorded in the wild	Not reported	Not reported	3		
Nymphaea thermarum	Magnoliopsida	2008	1987	Not reported	11		(*135*)
Ochrosia brownii	Magnoliopsida	2006	Not reported	Not reported	10		
Rhododendron kanehirai	Magnoliopsida	1984	Not reported	Not reported	5		
Senecio leucopeplus	Magnoliopsida	2007	Not reported	Not reported	1		

Sophora toromiro	Magnoliopsida	1960	1950-1956	1	17	Multiple failed reintroductions from 1965	(*136*, *137*)
Trochetiopsis erythroxylon	Magnoliopsida	1950s	Not reported	Not reported	9	1980s	

The collection history and present status of EW plant species held *ex situ*.

Table S5.

Species	Family	Order	Seed type predicted based on	Probability of recalcitrance	Predicted storage behaviour
Abutilon pitcairnense	Malvaceae	Malvales	Genus	0.002883	Orthodox
Aloe silicicola	Xanthorrhoeaceae	Asparagales	Genus	0.001743	Orthodox
Alphonsea hortensis	Annonaceae	Magnoliales	Family	0.513798	Recalcitrant
Amomum sumatranum	Zingiberaceae	Zingiberales	Family	0.012481	Orthodox
Arachis rigonii	Leguminosae	Fabales	Family	0.010307	Orthodox
Bromus bromoideus	Poaceae	Poales	Species	0	Orthodox
Bromus interruptus	Poaceae	Poales	Species	0	Orthodox
Brugmansia arborea	Solanaceae	Solanales	Family	0.00953	Orthodox
Brugmansia aurea	Solanaceae	Solanales	Family	0.032387	Orthodox
Brugmansia insignis	Solanaceae	Solanales	Family	0.157526	Orthodox
Brugmansia sanguinea	Solanaceae	Solanales	Family	0.019821	Orthodox
Brugmansia suaveolens	Solanaceae	Solanales	Family	0.128313	Orthodox
Brugmansia versicolor	Solanaceae	Solanales	Family	0.049257	Orthodox
Brugmansia vulcanicola	Solanaceae	Solanales	Family	0.032461	Orthodox
Camellia amplexicaulis	Theaceae	Ericales	Family	0.165695	Orthodox
Corypha taliera	Arecaceae	Arecales	Family	0.726928	Recalcitrant
Cyanea pinnatifida	Campanulaceae	Asterales	Genus	0.001267	Orthodox
Cyanea superba	Campanulaceae	Asterales	Genus	0.003024	Orthodox
Deppea splendens	Rubiaceae	Gentianales	Family	0.007442	Orthodox
Encephalartos brevifoliolatus	Zamiaceae	Cycadales	Order	0.009372	Orthodox
Encephalartos nubimontanus	Zamiaceae	Cycadales	Order	0.01957	Orthodox
Encephalartos woodii	Zamiaceae	Cycadales	Order	0.013487	Orthodox
Franklinia alatamaha	Theaceae	Ericales	Family	0.013332	Orthodox

Furcraea macdougallii	Asparagaceae	Asparagales	Family	0.012481	Orthodox
Kokia cookei	Malvaceae	Malvales	Family	0.040725	Orthodox
Lachanodes arborea	Compositae	Asterales	Family	0.012481	Orthodox
Lysimachia minoricensis	Primulaceae	Ericales	Species	0	Orthodox
Mangifera casturi	Anacardiaceae	Sapindales	Genus	0.877644	Recalcitrant
Mangifera rubropetala	Anacardiaceae	Sapindales	Genus	0.92769	Recalcitrant
Nymphaea thermarum	Nymphaeaceae	Nymphaeales	Genus	0.022476	Orthodox
Ochrosia brownii	Apocynaceae	Gentianales	Family	0.004237	Orthodox
Rhododendron kanehirai	Ericaceae	Ericales	Genus	0.059085	Orthodox
Senecio leucopeplus	Compositae	Asterales	Genus	0.001912	Orthodox
Sophora toromiro	Leguminosae	Fabales	Genus	0.006741	Orthodox
Trochetiopsis erythroxylon	Malvaceae	Malvales	Species	0	Orthodox

Modelled predictions of seed storage behaviour for 35 EW plant species.