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

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Teaser: A review of the hitherto overlooked statuses of Extinct in the Wild species reveals the perilous nature of the category.

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 animals, already compromised by their small number of founders, are maintained at sizes far below the thresholds necessary to ensure demographic security. Most EW plant species depend on live propagation by a small number of holders, with a minority secured at seed bank institutions. We show that both extinctions and recoveries are possible fates for EW species, and urgently call for international effort to drive toward the latter.

Main Text:

Despite a deepening crisis of species loss unprecedented in human history (*1*, *2*), international commitments to prevent extinction and improve the conservation status of all known threatened species have not been met (*3*). The field of conservation biology has, however, begun to demonstrate that the status of threatened species can be improved, and extinctions in the wild prevented and even reversed (*4*–*6*). These successes should encourage us that the post-2020 global biodiversity draft targets of arresting the increase in extinction rates and reducing the proportion of threatened species are within our capacity (*7*). A striking nexus of responsibility, vulnerability, and opportunity lies in those species 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) (*8*).

These organisms occupy a curiously overlooked space in our framework for evaluating and comparing risk of extinction. They are considered to be the species most at risk (*8*), but the viability of their populations is not assessed, nor, puzzlingly, is EW even classed as a "threatened" category. Beyond the recognition of the existence of *ex situ* populations for conferral of EW status, the Red List assessment process concerns itself solely with wild populations (*8*). Thus, while many extant species can be evaluated in detail and allocated threat categories according to the states of and trends in their geographic ranges and populations, we have so far ignored the extent of—and variation in—extinction risk of the very group of species for which humans are most responsible, and whose futures are amongst the least assured.

Here, we reveal the dynamic and often perilous state occupied by EW species. Though the EW category was first introduced by the IUCN in 1994 (*9*), we extend our analysis back to 1950 to provide an overview of the fates of the 96 species (53 animals and 43 plants) that are known to have persisted despite extirpation in the wild. We characterise the statuses of the *ex situ* populations of the 82 species (38 animals and 44 plants) that are currently (Red List version 2022-1 (*8*)) categorised as EW, as well as detailing their progress towards recovery through returns to the wild. We found that 10 species (five animals and five plants) currently regarded as EW should not qualify for the category: Two have gone extinct since their last assessment, 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 (Tables S5 and S6). This leaves 72 EW species (33 animals and 39 plants) we regard here as genuine.

To best contribute to eventual recovery in the wild, an *ex situ* population should be established using a representative set of founders, be maintained at a population size sufficient to minimise loss of genetic diversity, and spend as little time as practicable solely in an *ex situ* state (*10*, *11*). We found considerable variation and alarming deficiencies in these critical factors amongst EW species. 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 (*10*, *11*). 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 1). Most *ex situ* populations of EW species were thus imperiled to begin with, and require large populations to enhance demographic security and reach a point at which populations can be maintained to minimize loss of the genetic diversity that remains (Fig. 3A).

What constitutes a size above which a population is considered viable is highly context specific, depending on the biology of the species, aspects of its management and environment, as well as varying definitions of “viable” (*12*). 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) (*13*), 4169 (standardised to a 99% probability of persistence over 40 generations) (*14*), and 5816 (for a 99% probability of persistence over 40 generations in vertebrate species) (*15*), with wide and positively-skewed distributions. Considering the maintenance of genetic diversity for a context in which supplementation 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 (*16*). Given that the ratio of effective population size to census population size (N_e/N) has been estimated to average 0.26 in *ex situ* populations of threatened animals (*17*), this implies that most populations should exceed 1900 individuals at the very least (*18*). These figures do not represent universal thresholds delineating viable populations from lost causes, rather standards that enable us to highlight populations that may be at risk, and thus demanding of our attention. In this light, the shortfall for EW species is stark: population estimates are not available for plants, but of the 30 EW animal species currently maintained in *ex situ* institutions for which we could find data, just

6 have populations exceeding 1900 individuals, and half have census population sizes lower even than the minimum advised N_e of 500 (Fig. 1).

On the other hand, *ex situ* populations that do manage to reach larger sizes are further challenged by adaptation to the conditions of *ex situ* care (*19*, *20*), creating a trade-off between demographic security and the suitability of individuals for release. Distributing populations across multiple collections may help mitigate against such adaptation (*21*) and provide a buffer against institutional-level risks such as disease outbreaks, catastrophes, and the financial insecurity and logistical challenges deepened by the impacts of COVID-19 (*19*, *22*). Again, worryingly, the majority of animal (at least 23/30, 77%) and plant (20/37, 54%) EW species for which information is available are held at fewer than 10 institutions, and six plant species are held at just a single institution (Fig. 2).

However, distributing an EW species across several holders brings with it the potential of fragmenting an already compromised population into a set of smaller isolated groups. For *ex situ* animal populations, formalised cooperative breeding programs—EAZA *Ex situ* Programmes (EEPs) in Europe, Species Survival Plans (SSPs) predominantly in North America, and Species Management Programs (SMPs) in Australasia—seek to manage each species as a metapopulation by planning and coordinating breeding and transfers between institutions within their respective regions. 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 (*23*). Despite their obvious relevance, 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 S8). Even for species covered by a cooperative breeding program, implementation of management decisions can be challenging: a recent analysis found that SSP recommendations to transfer individuals were fulfilled just 57% of the time, while the fulfilment rate of recommendations for specific animals to breed was even lower at 20% (*24*). 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 S8). Those missing studbooks were fish, amphibian, and invertebrate species, 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 (*25*), as is deployed for the *Partula* snail species in our dataset (*17*, *26*). 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 (*27*). Efforts to address these problems and develop pedigree-based metapopulation management techniques for plants are currently underway (*27*, *28*). Underpinning all of these efforts should be an examination of how populations are expected to respond to current and proposed management across the coming decades. 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 S8).

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 (*29*), this technique—which can retain seed viability for potentially hundreds of years (*30*)—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 (*31*). Using a seed storage prediction model (*32*), we found that approximately 89% (31 of 35 species modelled, see Table S9) of EW plant species are predicted to produce desiccation-tolerant seeds suitable for seed banking. Despite this—and while acknowledging that botanic gardens may retain some material as seed—we report that only 28% (11/39) of EW plant species are represented in seed bank institutions (Fig. 2).

Irrespective of the technique, however, *ex situ* preservation 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. Taken together, these insights highlight the urgent need to find ways to re-establish populations into the wild. We find that, while conservation translocations back to wild settings have been undertaken for only 26% 11/43) of historically (1950-2022) *ex situ*-restricted and 23% (9/39) of currently EW plant species, they have been deployed for the majority of both historically *ex situ*-restricted (32/53, 60%) and currently EW (22/33, 67%) animal species (Fig. 3). While this is certainly encouraging, it leaves 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 (*33*), is approaching a century—approximately 37 generations—in *ex situ* care.

The EW state can thus represent a crucial waypoint on the pathway to recovery. Since 1950, 96 species (53 animals and 43 plants) have met the conditions of EW (i.e., have been restricted to *ex situ* maintenance, Figs. 3B and 3C). 83 of these (42 animals and 41 plants) have been listed on the Red List as EW. 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. These include the Jaramago de Alborán (*Diplotaxis siettiana*), now Critically Endangered (CR), 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 having been restricted to *ex situ* care. These include the St Helena olive (*Nesiota elliptica*) and the Pinta giant tortoise (*Chelonoidis abingdonii*), both lost under our care in the last decade (Fig. 3).

We necessarily restricted our investigation of *ex situ* holdings to species currently assessed on the Red List as EW, but this likely under-represents the true number of species that sit in this category or may soon enter it. For example, a further 58 species (46 plants and 12 animals) are assessed as CR (Possibly Extinct in the Wild) (*8*). In addition, the often slow pace of changes in Red List status (*34*) combines with a conservative approach to declaring extinction (*35*) 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 (*36*), 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 ‘ālula (*Brighamia insignis*) , a shrub native to Hawaii and assessed as CR (Possibly Extinct in the Wild), the Vietnam pheasant (*Lophura edwardsi*) (*37*), and the Javan pied starling (*Gracupica jalla*) (*38*), the latter two both currently CR without 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 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 (*39*)? 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 (*40*) while still being assessed as EW. An improved system for assessing the health and progress of EW species would be both beneficial and feasible.

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 space 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 (*41*). 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 (*42*). 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 (*43*). 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 ‘akikiki (*Oreomystis bairdi*), with an estimated wild population in 2021 of just 45 individuals (*43*). However, the location of *ex situ* facilities must balance Native Hawaiians’ preference not to remove birds from Hawai’i (*43*). 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 (*44*). 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 (knowledge) 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 (*45*).

Similarly, *ex situ* institutions 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. 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" (*46*), which has not, as far as we can identify, been adopted for any EW species. We acknowledge that 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 (*47*). 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 (*48*, *49*). For example, Christmas Island blue-tailed skinks (*Cryptoblepharus egeriae*) have been released to the wild on the Cocos (Keeling) islands (*50*) and proposals for sihek releases on Palmyra Atoll are under consideration (*51*). 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 *Partula* 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*) (*52*). Rather than give up, those involved in *Partula* snail recovery are learning and modifying how to best attempt new releases and reinforce all wild populations. With sustained support and adaptive management, the *Partulas* 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.

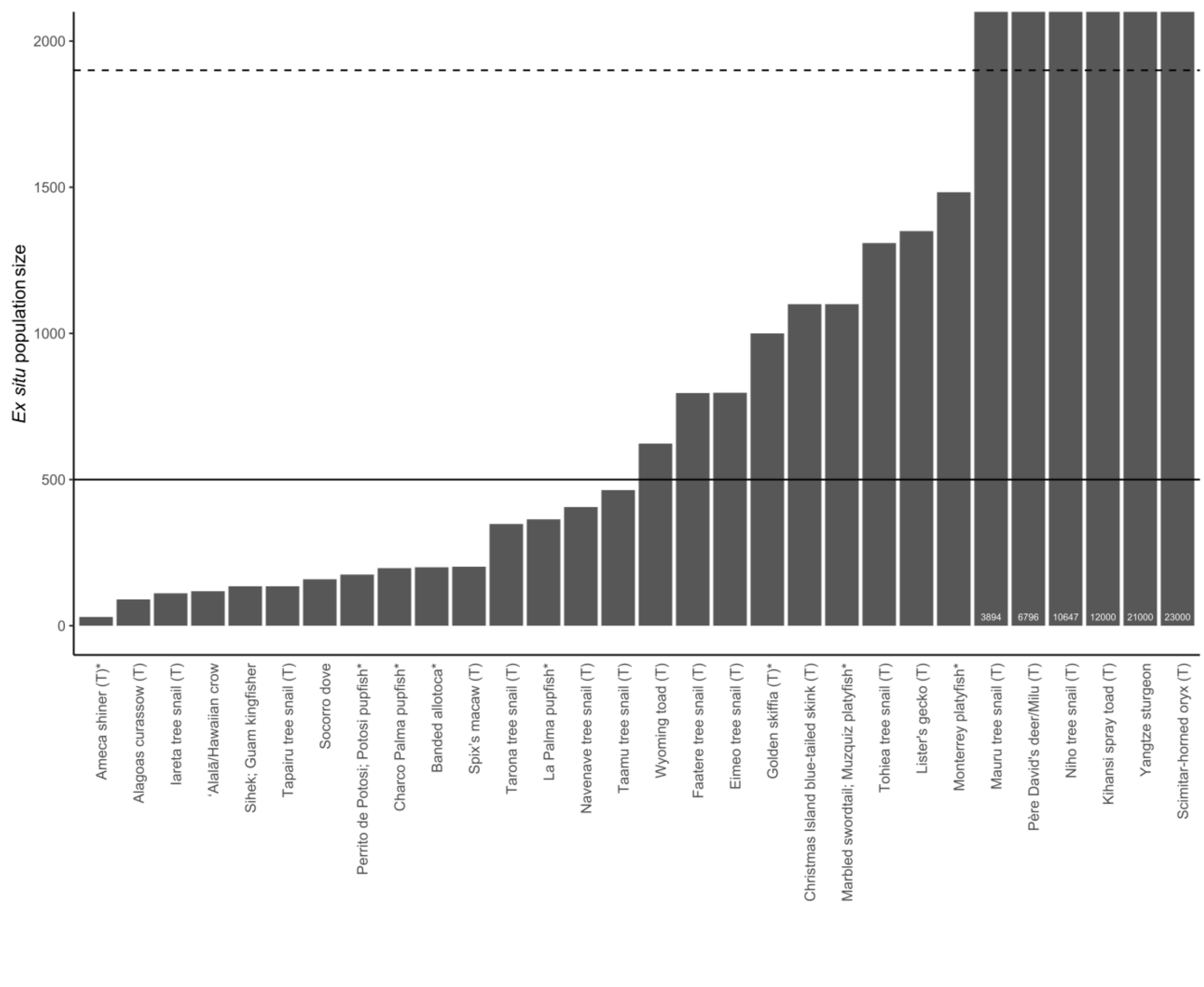

Fig. 1. Estimated *ex situ* population sizes of EW animal species. Solid horizontal line: Minimum N_e recommended to minimise loss of genetic diversity (500). Dashed horizontal line: minimum census population size expected to ensure effective population size of 500 (1900 individuals, see (*18*)). Where 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) (*53*), 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.

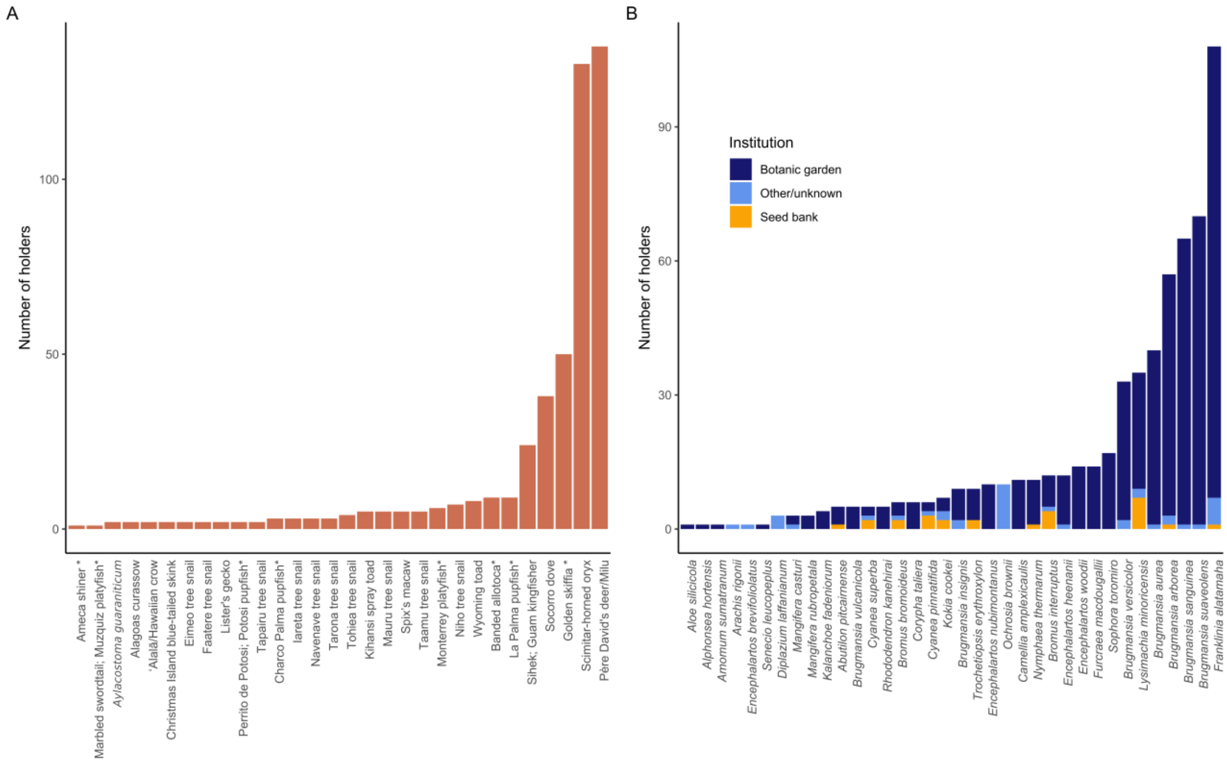

Fig. 2. Holders of *ex situ* EW species. Panel A: Estimates number of holders for 30 of the 32 EW animal species held *ex situ.* Estimates produced as for Fig. 1. Species marked with an asterisk (*) may have additional individuals kept by hobbyists. Panel B: Estimates for number and type (botanical garden, 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 (*54*) combined with academic and grey literature, and advice from relevant taxon experts and conservation practitioners.

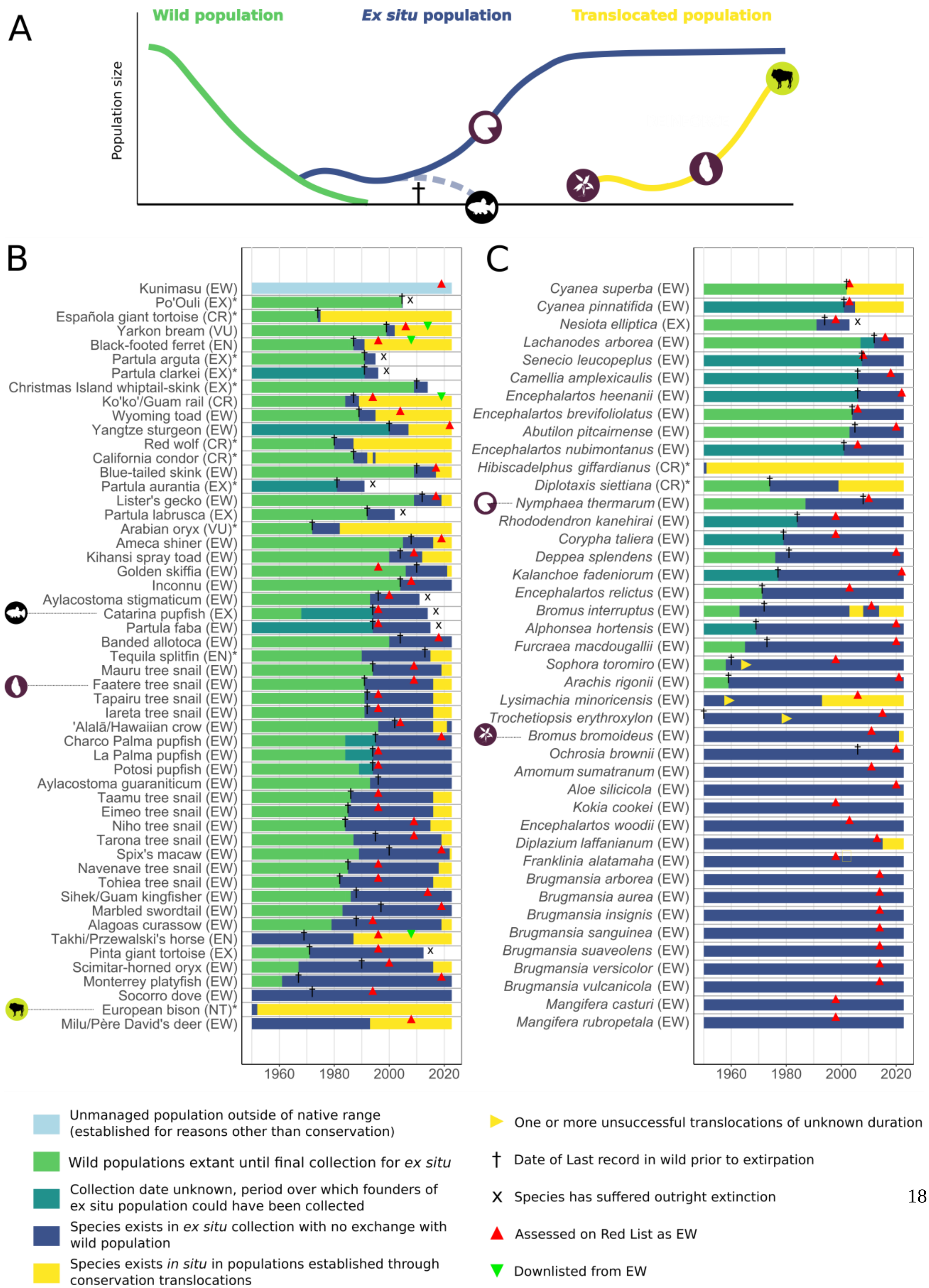
A
Wild population
Ex situ population
Translocated population
Population size
B
Kunimasu (EW)
Po'Ouli (EX)*
Española giant tortoise (CR)*
Yarkon bream (VU)
Black-footed ferret (EN)
Partula arguta (EX)*
Partula clarkei (EX)*
Christmas Island whiptail-skink (EX)*
Ko'ko'/Guam rail (CR)
Wyoming toad (EW)
Yangtze sturgeon (EW)
Red wolf (CR)*
California condor (CR)*
Blue-tailed skink (EW)
Partula aurantia (EX)*
Lister's gecko (EW)
Partula labrusca (EX)
Arabian oryx (VU)*
Ameca shiner (EW)
Kihansi spray toad (EW)
Golden skiffia (EW)
Inconnu (EW)
Aylacostoma stigmaticum (EW)
Catarina pupfish (EX)
Partula faba (EW)
Banded allotoca (EW)
Tequila splitfin (EN)*
Mauru tree snail (EW)
Faatere tree snail (EW)
Tapairu tree snail (EW)
Iareta tree snail (EW)
'Alalā/Hawaiian crow (EW)
Charco Palma pupfish (EW)
La Palma pupfish (EW)
Potosi pupfish (EW)
Aylacostoma guaraniticum (EW)
Taamu tree snail (EW)
Eimeo tree snail (EW)
Niho tree snail (EW)
Tarona tree snail (EW)
Spix's macaw (EW)
Navenave tree snail (EW)
Tohiea tree snail (EW)
Sihek/Guam kingfisher (EW)
Marbled swordtail (EW)
Alagoas curassow (EW)
Takhi/Przewalski's horse (EN)
Pinta giant tortoise (EX)
Scimitar-horned oryx (EW)
Monterrey platyfish (EW)
Socorro dove (EW)
European bison (NT)*
Milu/Père David's deer (EW)
1960
1980
2000
2020
C
Cyanea superba (EW)
Cyanea pinnatifida (EW)
Nesiota elliptica (EX)
Lachanodes arborea (EW)
Senecio leucopeplus (EW)
Camellia amplexicaulis (EW)
Encephalartos heenanii (EW)
Encephalartos brevifoliolatus (EW)
Abutilon pitcairnense (EW)
Encephalartos nubimontanus (EW)
Hibiscadelphus giffardianus (CR)*
Diplotaxis siettiana (CR)*
Nymphaea thermarum (EW)
Rhododendron kanehirai (EW)
Corypha taliera (EW)
Deppea splendens (EW)
Kalanchoe fadeniorum (EW)
Encephalartos relictus (EW)
Bromus interruptus (EW)
Alphonsea hortensis (EW)
Furcraea macdougallii (EW)
Sophora toromiro (EW)
Arachis rigonii (EW)
Lysimachia minoricensis (EW)
Trochetiopsis erythroxylon (EW)
Bromus bromoideus (EW)
Ochrosia brownii (EW)
Amomum sumatranum (EW)
Aloe silicicola (EW)
Kokia cookei (EW)
Encephalartos woodii (EW)
Diplazium laffanianum (EW)
Franklinia alatamaha (EW)
Brugmansia arborea (EW)
Brugmansia aurea (EW)
Brugmansia insignis (EW)
Brugmansia sanguinea (EW)
Brugmansia suaveolens (EW)
Brugmansia versicolor (EW)
Brugmansia vulcanicola (EW)
Mangifera casturi (EW)
Mangifera rubropetala (EW)
1960
1980
2000
2020
Unmanaged population outside of native range (established for reasons other than conservation)
Wild populations extant until final collection for ex situ
Collection date unknown, period over which founders of ex situ population could have been collected
Species exists in ex situ collection with no exchange with wild population
Species exists in situ in populations established through conservation translocations
One or more unsuccessful translocations of unknown duration
† Date of Last record in wild prior to extirpation
X Species has suffered outright extinction
Assessed on Red List as EW
Downlisted from EW

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. 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 represented)	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
‘Alalā (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		

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Acknowledgments: We are very grateful to three anonymous reviewers for their thorough review of this manuscript, and insightful and constructive guidance in improving it. We thank the following taxon experts for providing details on the conservation history and present status of species we investigated: Monika Böhm, Ian Burfield, Alex Cliffe, John Donaldson, Jon-Paul Emery, Frank Howarth, Michael Koeck, Camile Lugarini, David Mallon, Bryce Masuda, Tim Pearce, Paul Pearce-Kelly, Sean Putney, Manuel G. Quintana, Markita Savage, Stefan Stadler, and Amanda Trask. Species icons, all public domain, were obtained from phylopic.org and were produced by Thomas G. Barnes, Margot Michaud, Eric Moody, Felix Vaux, and Steven Traver.

Funding: DS and JGE acknowledge funding from Research England. Abby Meyer acknowledges funding from U.S. Botanic Garden.

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Competing interests: Authors declare that they have no competing interests.

Data and materials availability: All data are available in the main text or the supplementary materials.

Supplementary Materials

Materials and Methods

Tables S1 to S10

Supplementary Materials for

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

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This PDF file includes:

Materials and Methods

Tables S1 to S10

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) (*8*). 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" (*55*). 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, and this state is not the primary focus of this study. In approximating the start of modern species conservation, 1950 was chosen as a cut-off date for inclusion (following the approach used by Akçakaya *et al*. (*56*)). 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 82 species (38 animals and 44 plants) currently categorised as EW were extracted from the Red List version 2022-1 (*8*). Species that were formerly EW but have since gone extinct (three animal species, Table S1) or have been downlisted to another category (i.e., an improvement in conservation status: four animal species, Table S2) were compiled from IUCN summary statistics for genuine status changes (*8*). We then identified additional species that would have been *ex situ*-restricted for any period of time 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 S3 for the five species that have since gone extinct, and Table S4 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 S1).

Confirmation of extinction in the wild is an exhaustive process (*35*) 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. However, the Red List is limited in timeliness and reach: the assessments for approximately a third of Critically Endangered species are more than a decade old, for example, and the majority of species remain unevaluated (*8*). We therefore emphasize that our approach necessarily restricts our study to the best understood sub-set of the species to which the issues with which we are concerned pertain. 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 consider any reported extinction in *ex situ* care of a species already assessed as EW to be unambiguous, however, and incorporate these where relevant (see Table S5). We excluded eight species (three animals and five plants) currently assessed as EW whose assessments appear erroneous or superseded by reports of wild populations (see Table S6 for the list of these species alongside the rationale for their removal).

For the resulting 96 species (53 animals and 43 plants) that we regard as having been *ex situ*-restricted since 1950, we then 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 (*48*), 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 (*48*). Where this information was not contained in a Red List assessment, we sought it from recovery project documentation, academic literature, and by contacting relevant taxon experts and conservation practitioners. 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 S2-S8.

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 April 25th 2022 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 (*53*). 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) (*57*), the European Association of Zoos and Aquaria's list of EEPs (*58*), Australasia's Zoo Aquarium Association's list of Species Management Programs (SMPs) (*59*), and the World Association of Zoos and Aquariums' list of Global Species Management Plans (*23*). 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 (*54*). 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*. 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 any information on the *ex situ* populations of three EW species (one animal and two plants, see Table S7 for details). Through this approach we have collated the most comprehensive and relevant overview of the *ex situ* populations of EW species feasible. However, we acknowledge that some holdings remain beyond the reach of our survey, specifically those 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). However, we do not expect that any extra material held in such contexts would significantly alter the population summaries provided in Fig. 1 and Fig. 2.

To predict the seed storage behaviour of EW plant species, we applied the model developed by Wyse and Dickie (*32*). 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 S9 for detailed model output.

Table S1.

Scientific name	**Common name**	**Kingdom**	**Class**	**Last reported in wild**	**Number of individuals collected (of which, number of founders represented)**	**Year extinct**	**Year reclassified as extinct**
Chelonoidis abingdonii	Pinta giant tortoise	Animals	Reptilia	1971	1	2012	2016
Megupsilon aporus	Catarina pupfish	Animals	Actinopterygii	1994	Not reported	2014	2019
Nesiota elliptica	St Helena olive	Plants	Magnoliopsida	1994	1	2003	2004
Partula labrusca		Animals	Gastropoda	1992	Not reported	2002	2009

Species formerly assessed as EW that are now assessed as Extinct.

Table S2.

Scientific name	**Common name(s)**	**Kingdom**	**Class**	**Last reported in wild**	**Number of individuals collected (of which, number of founders represented)**	**Year conservation translocations started (R: Reintroduction, AC: Assisted Colonization)**	**Year downlisted**	**Red List 2022-1 status**	**Additional references**
Acanthobrama telavivensis	Yarkon bream	Animalia	Actinopterygii	1999	150	R: 2002	2014	VU	(*60*)
Equus ferus	Takhi; Przewalski's Horse	Animalia	Mammalia	1969	53 (12)	R: 1997	2008	EN	
Hypotaenidia owstoni	Ko'ko'; Guam Rail	Animalia	Aves	1987	22	AC: 1989 R: 1998	2019	CR	(*61*)
Mustela nigripes	Black-footed Ferret	Animalia	Mammalia	1987	18 (7)	R: 1991	2008	EN	

* Key to Red List categories: CR: Critically Endangered; E: Endangered (pre-1994 category); EN: Endangered; EX: Extinct; NT: Near Threatened; T: Threatened (pre-1994 category); VU: Vulnerable

Species formerly assessed as EW that have experienced genuine improvements in Red List status.

Table S3

Scientific name	Common name	Kingdom	Class	Year last recorded in wild	Extinction year	Published Red List assessments	Notes	Additional references
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.	(*62*)
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.	(*63*)

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.	(*26*, *64*, *65*)
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	(*66*–*68*)
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	(*26*, *69*)

							microsporidian parasites (*69*), but the causal agent has since been questioned (*26*).	

* Key to Red List categories: CR: Critically Endangered; E: Endangered (pre-1994 category); EN: Endangered; EX: Extinct; NT: Near Threatened; T: Threatened (pre-1994 category); VU: Vulnerable

Formerly *ex situ*-restricted species that were never assessed as EW and are now extinct.

Table S4.

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
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.	(*70, 71*)

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.	(*72*)
Chelonoidis hoodensis	Española giant tortoise	Animals	Reptilia	1974	15 (15)	R: 1975 AC: 2015	CR (2017, 2016, 1994 as *Geochelone nigra hoodensis*)	Endemic to Española, the Galápagos Islands, exploitation for human consumption and habitat degradation drove the wild population to a low 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.	(*73, 74*)
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.	(*4*)

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.	(*75*)
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.	(*76*)
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	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	(*77*)

							decreasing in numbers" (1965).	as individuals from the USA herd. In 1993, the global population was reported to be derived from 17 wild-caught founders.	
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.	

* Key to Red List categories: CR: Critically Endangered; E: Endangered (pre-1994 category); EN: Endangered; EX: Extinct; NT: Near Threatened; T: Threatened (pre-1994 category); VU: Vulnerable

Formerly *ex situ*-restricted species that were never assessed as EW and have since returned to the wild.

Table S5.

Scientific name	**Kingdom**	**Class**	**Year last recorded in wild**	**Extinction year**	**Notes**	**Additional references**
Aylacostoma stigmaticum	Animals	Gastropoda	1996	2011	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.	
Partula faba	Animals	Gastropoda	1994	2015	Endemic to Raiatea and Tahaa, this species was extirpated from the wild after introduction of the carnivorous snail *Euglandina rosea*. Was maintained *ex situ* as part of an international project conserving multiple Partula species from the Society Islands, but the last individual of this species died in *ex situ* care in 2015.	(*26*)

Species currently assessed (Red List 2022-1) as EW that have gone extinct since their most recent assessment

Table S6.

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.	(*78*, *79*)
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.	(*80*)
Dombeya rodriguesiana	Plants	Magnoliopsida	Extant in wild	Following IUCN Red List Categories and Criteria version 3.1 (*55*), 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.	(*55*, *81*)
Euphorbia mayurnathanii	Plants	Magnoliopsida	Synonym	Synonym of *Euphorbia antiquorum*, which is assessed as Least Concern.	(*78*)

Erythroxylum echinodendron	Plants	Magnoliopsida	Synonym	Synonym of *Erythroxylum minutifolium*, which is extant in the wild in Cuba	(*78*, *82*)
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.	
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.	(*83*)

Species currently assessed (Red List 2022-1) as EW regarded in this study as erroneous.

Table S7.

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.	(*84*)
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.	(*85*)

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

Table S8.

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	(*86*)
*Allotoca goslinei**	Banded allotoca	Actinopterygii	2004	2000	Not reported	200	<10	EEP, studbook		
Anaxyrus baxteri	Wyoming toad	Amphibia	1989	1989	10	623	8	SSP, studbook	R: 1995	(*87*)
Aylacostoma guaraniticum		Gastropoda	1996	1993	Not reported	Unknown	2			

Corvus hawaiiensis	ʻAlalā; Hawaiian crow	Aves	2002	1970-1996	(9)	118	2	Studbook	R: 2016 (recaptured 2020)	(*88*, *89*)
Cryptoblepharus egeriae	Blue-tailed skink	Reptilia	2010	2009	66	1100	2	PVAs used to guide harvesting for translocations	R: 2017 AC: 2019	(*50*, *62*, *90*)
Cyanopsitta spixii	Spix's macaw	Aves	2000	1976	17 (7)	202	5	Studbook	R: 2022	(*91*)
*Cyprinodon alvarezi**	Perrito de Potosi; Potosi pupfish	Actinopterygii	1994	1989	Not reported	175	2	EEP		(*92*)
*Cyprinodon longidorsalis**	La Palma pupfish	Actinopterygii	1994	After 1984 (discovery) and before 1994 (extirpation)	Not reported	364	9	EEP		
*Cyprinodon veronicae**	Charco Palma pupfish	Actinopterygii	1995	After 1984 (discovery) and before	Not reported	197	3	EEP		

				1995 (extirpation)						
Elaphurus davidianus	Milu; Père David's deer	Mammalia	1868	Unknown	18 (11)	6796	138	SSP, studbook	R: 1993	(*40*, *93*)
Lepidodactylus listeri	Lister's gecko	Reptilia	2012	2009	43	1350	2	Studbook. PVAs used to guide harvesting for translocations	R: 2019	(*62*, *90*)
Mitu mitu	Alagoas curassow	Aves	1988	1979	5 (3)	90	2	Studbook	R: 2019	(*94*, *95*)
Nectophrynoides asperginis	Kihansi spray toad	Amphibia	2004	2000	499	12000	5		R: 2012	(*96*, *97*)
*Notropis amecae**	Ameca shiner	Actinopterygii	2008	2005	6	30	1		R: 2016	(*98*)
Oryx dammah	Scimitar-horned Oryx	Mammalia	Late 1980s, early	1937 - 1967	48-60	Approximately 23000	>133	SSP, EEP, SMP, studbook. PVAs previously conducted, but not	R: 2016 (Considered here as first attempt to establish a wild population. However, releases into semi-wild	(*99*–*104*)

			1990s					used to manage global population.	contexts have taken place since 1985.)	
*Partula garrettii (*reclassified from *P. tristis)*	Iareta tree snail	Gastropoda	1992	1991	Not reported	111	3	EEP, studbook.	R: 2016	(*26*, *52*)
Partula hebe	Tapairu tree snail	Gastropoda	1992	1991	Not reported	135	2	EEP, studbook.	R: 2016	(*26*, *52*)
Partula mirabilis	Navenave tree snail	Gastropoda	1985	1984 - 1985	Not reported	406	3	EEP, studbook.	R: 2018	(*26*, *52*)
Partula mooreana	Eimeo tree snail	Gastropoda	1985	1985	Not reported	797	2	EEP, studbook.	R: 2016	(*26*, *52*, *66*)
Partula navigatoria	Faatere tree snail	Gastropoda	1991	1991	Not reported	796	2	EEP, studbook.	R: 2016	(*26*, *52*)
Partula nodosa	Niho tree snail	Gastropoda	1984	1984	Not reported	10647	7	EEP, studbook.	R: 2015	(*26*, *66*)
Partula rosea	Tarona tree snail	Gastropoda	1987	1987	Not reported	348	3	EEP, studbook.	R: 2019	(*26*, *105*)

Partula suturalis	Taamu tree snail	Gastropoda	1986	1980 - 1986	Not reported	464	5	EEP, studbook.	R: 2016	(*26*, *52*)
Partula tohiveana	Tohiea tree snail	Gastropoda	1982	1982	Not reported	1309	4	EEP, studbook.	R: 2016	(*26*, *52*, *66*)
Partula varia	Mauru tree snail	Gastropoda	1994	1991 - 1994	Not reported	3894	5	EEP, studbook.	R: 2019	(*26*, *105*)
*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.		(*106*, *107*)
*Xiphophorus couchianus**	Monterrey platyfish	Actinopterygii	1967	1961	Not reported	1483	6	Studbook		(*108*)
*Xiphophorus meyeri**	Marbled swordtail; Muzquiz platyfish	Actinopterygii	1997	1983	Not reported	Approximately 1100	>1	Studbook		(*108*)

Zenaida graysoni	Socorro dove	Aves	1972	1925	17	159	38	EEP, studbook		(*33*, *109*)

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 S9.

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		(*110*)
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	2021	(*111*)
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	(*112*)
Cyanea superba	Magnoliopsida	Around 2000	Not reported	3	5	1998	(*113*)
Deppea splendens	Magnoliopsida	1981	1976	Not reported	Unknown		(*114*)
Diplazium laffanianum	Polypodiopsida	1905	Not reported	5	3	2014	(*115*)
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		(*84*)
Encephalartos woodii	Cycadopsida	1916	Not reported	1	14		
Franklinia alatamaha	Magnoliopsida	1803	Not reported	Not reported	108	2002	(*116*)
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		(*117*)
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	(*118*, *119*)
Trochetiopsis erythroxylon	Magnoliopsida	1950s	Not reported	Not reported	9	1980s	

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

Table S9.

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 cookie	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 brownie	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