PHILOSOPHICAL TRANSACTIONS B

SUPPLEMENTARY MATERIAL to

Unshifting the baseline: a framework for documenting historical population changes and assessing long-term anthropogenic impacts

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Additional background and examples of applications, including:

- Background on the IUCN Red List of Threatened Species
- Rationale for category thresholds of significant population change
- Examples of preliminary baseline assessments
- Detailed baseline assessments of subpopulations of bowhead whale, *Balaena mysticetus*

Background on the IUCN Red List of Threatened Species

The proposed framework of baseline assessments is strongly inspired by, and complementary to, the IUCN Red List of Threatened Species [1]. It was also designed to improve compatibility between the two frameworks, namely in the thresholds between categories. We thus provide here background information on the IUCN Red List needed to better understand the rationale underpinning our proposed framework.

The IUCN Red List, produced by the International Union for Conservation of Nature Red List Partnership, is one of the most important conservation tools available today [2,3]. An authoritative system for categorising species according to their risk of extinction, its application to thousands of species has shed light on the magnitude and spatial distribution of species risk of extinction across taxa and across regions (e.g., [4–6]).

A species' Red List assessment consists of its classification into a category of extinction risk (Supplementary Figure 1), accompanied by the rationale for listing and supporting documentation [7]. For the three categories of threat (Vulnerable, Endangered, Critically Endangered), classifications are determined by applying a set of quantitative criteria (A to E; Supplementary Figure 1). Criterion E is based on extinction probability within a specified timeframe (as assessed through quantitative studies such as population viability analyses; Supplementary Figure 1) but its application requires data on demography and environmental variability that are seldom available, and so in practice Criterion E is very rarely used in IUCN Red List assessments. Instead, assessments that use Criteria A to D focus on three general indicators of extinction risk: rate of population decline (Criterion A), scale of geographic range (Criteria B and D2), or population size (Criterion C and D1). The latter two can be a sign of extinction risk on their own if small enough (Criterion D), or if combined with aggravating factors (declining numbers, fluctuation, or particular population structure) (Supplementary Figure 1). The species' biology enters into these assessments to provide a meaningful temporal scale against which to assess whether rates of population decline (Criterion A) are concerning given the species' capacity for population recovery: rates are measured over ten years or three generations, whichever is longer.

This simplicity has made it possible to carry out Red List assessments of taxa with very different life histories and a wide range of threatening factors, and even for species for which very little is known about their biology. For example, evaluating population declines under Criterion A does not necessarily involve direct observation of population size; it can instead be estimated, inferred or suspected based on an index of abundance appropriate to the taxon, a decline in area of occupancy, extent of occurrence and/or quality of habitat, actual or potential levels of exploitation, or the effects of introduced taxa, hybridization, pathogens, pollutants [7].

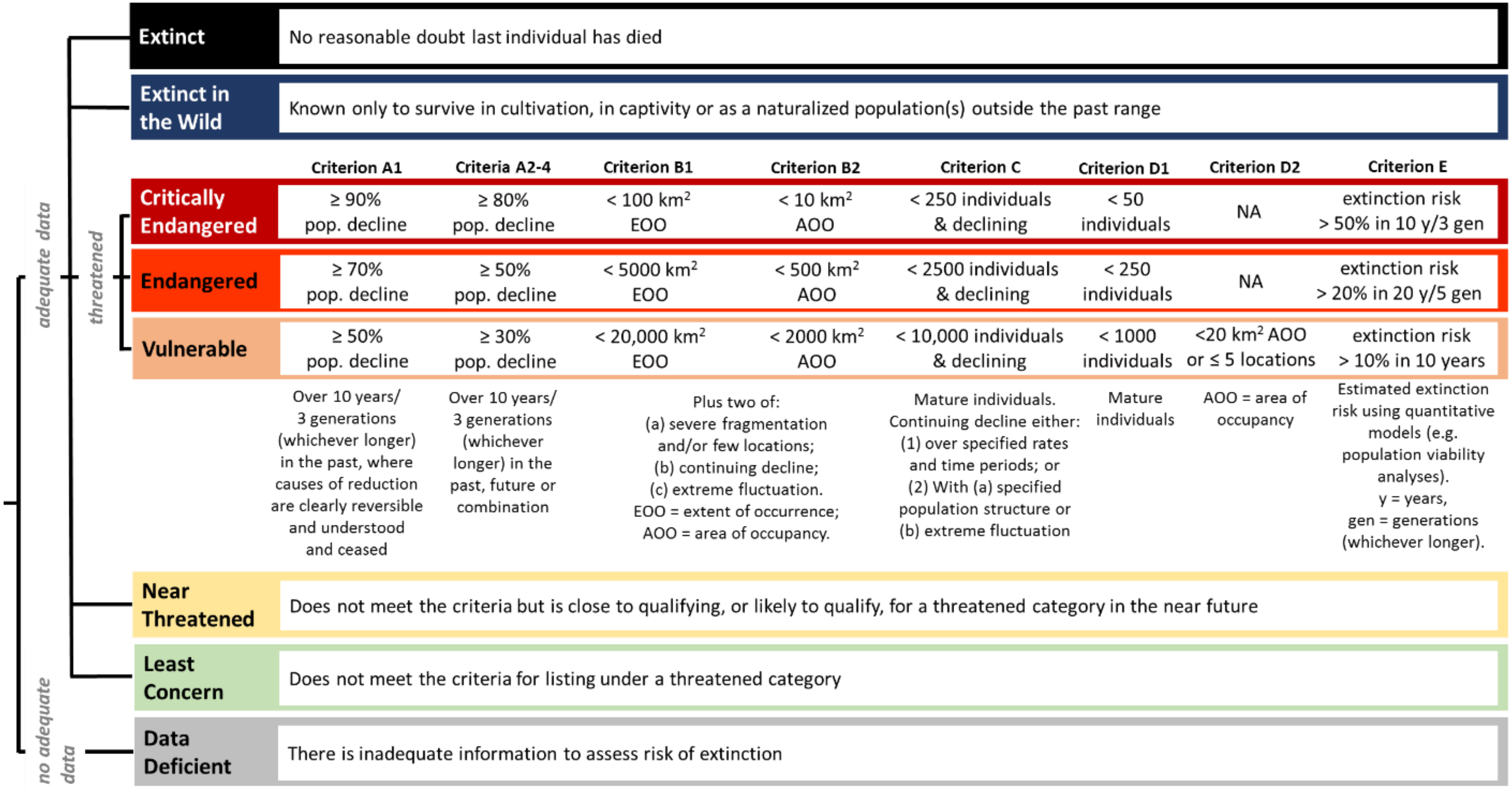

Figure S1: IUCN Red List Categories, and a simplified overview of the IUCN Red List Criteria (adapted from [2,7]). In addition, the Category "Not Evaluated" applies to all taxa not yet evaluated against the criteria.

Data on species abundances and distributions are key to Red List assessments, but only inasmuch as they provide information on risk of extinction, rather than on how they relate to baselines of natural abundances or original range sizes. For example, a rapid decline in population size or range size triggers Criterion A thresholds because it reflects ongoing threats capable of quickly driving the species to extinction. If however the population subsequently stabilises at not-too-low levels (i.e. above the thresholds of range size or population size that trigger Criteria B, C, or D), then the risk of extinction abates, and accordingly – and rightfully so – the species will be classified as Least Concern. Hence, by purpose and by design [8], the Red List does not keep a "memory" of cumulative changes in species abundances or distributions. It is also blind to slow long-term population declines (slower than 30% over 10 years/three generations), again as long as the population and geographic range stay above certain thresholds of small population or range size. The latter are not in the Red List as indicators of depletion in relation to a baseline, but as indicators of high risk of extinction (either on their own – Criterion D – or in combination with other aggravating factors – Criteria B, C). None of this diminishes the value of the Red List assessments as indicators of extinction risk, but it underscores the fact that they are not intended as measures of past human impacts on species and it reinforces the value of a complementary assessment tool dedicated to this purpose.

Rationale for category thresholds of significant population change

EPOCH assessments can be undertaken at the level of whole species, or at the level of infra-specific subpopulations. For simplicity, we generally use throughout the term 'populations' to refer both types of assessment units, with 'population size' referring to the number of all individuals in the assessed unit.

The proposed EPOCH classification system includes one category of no significant population change (Little Changed), five categories of substantial depletion (Moderately Depleted; Highly Depleted; Severely Depleted; Nearly Extirpated; Extirpated), four categories of substantial increase (Moderately Increased; Highly Increased; Severely Increased; Newly Present), and a category to account for cases when it is not possible to evaluate population change (Undetermined; Figure 1).

The thresholds for the five categories of substantial depletion were selected to give increasing resolution (i.e. the classes become narrower) as populations approach extirpation (Figure S2), while matching as possible with the thresholds of IUCN Red List's Criterion A2. Hence, a threshold of 30% decline marks the transition from Little Changed to Moderately Depleted (Figure 1) to match the transition in the IUCN Red List from Least Concern to Vulnerable (Figure S1). Similarly, a threshold of 80% decline marks the transition from Highly Depleted to Severely Depleted (Figure 1), as well as the transition from Endangered to Critically Endangered in the IUCN Red List (Figure S1). The category of Extirpated is equivalent to the IUCN Extinct category, covering populations for which there is (historical and/or archaeological) evidence that the species it was previously established in the region, but it is longer present (as determined from recent appropriate surveys that have failed to record individuals, or from a lack of observations in recent decades), other that extremely rare observations likely corresponding to vagrant individuals. Critically Endangered taxa flagged as "Possibly Extinct" in the IUCN Red List (which on the balance of evidence, are likely to be extinct, but for which there is a small chance that they may be extant) [9] fall in the proposed scheme under the Nearly Extirpated category.

Regarding the categories of substantial increase, thresholds are such that they give higher resolution to lower rates of increase. The first threshold, of 30% increase, was chosen to be symmetrical to the transition towards substantial depletion. The second corresponds to a doubling of the population (100% increase), and the third to an increase by an order of magnitude (> 1000 % increase).

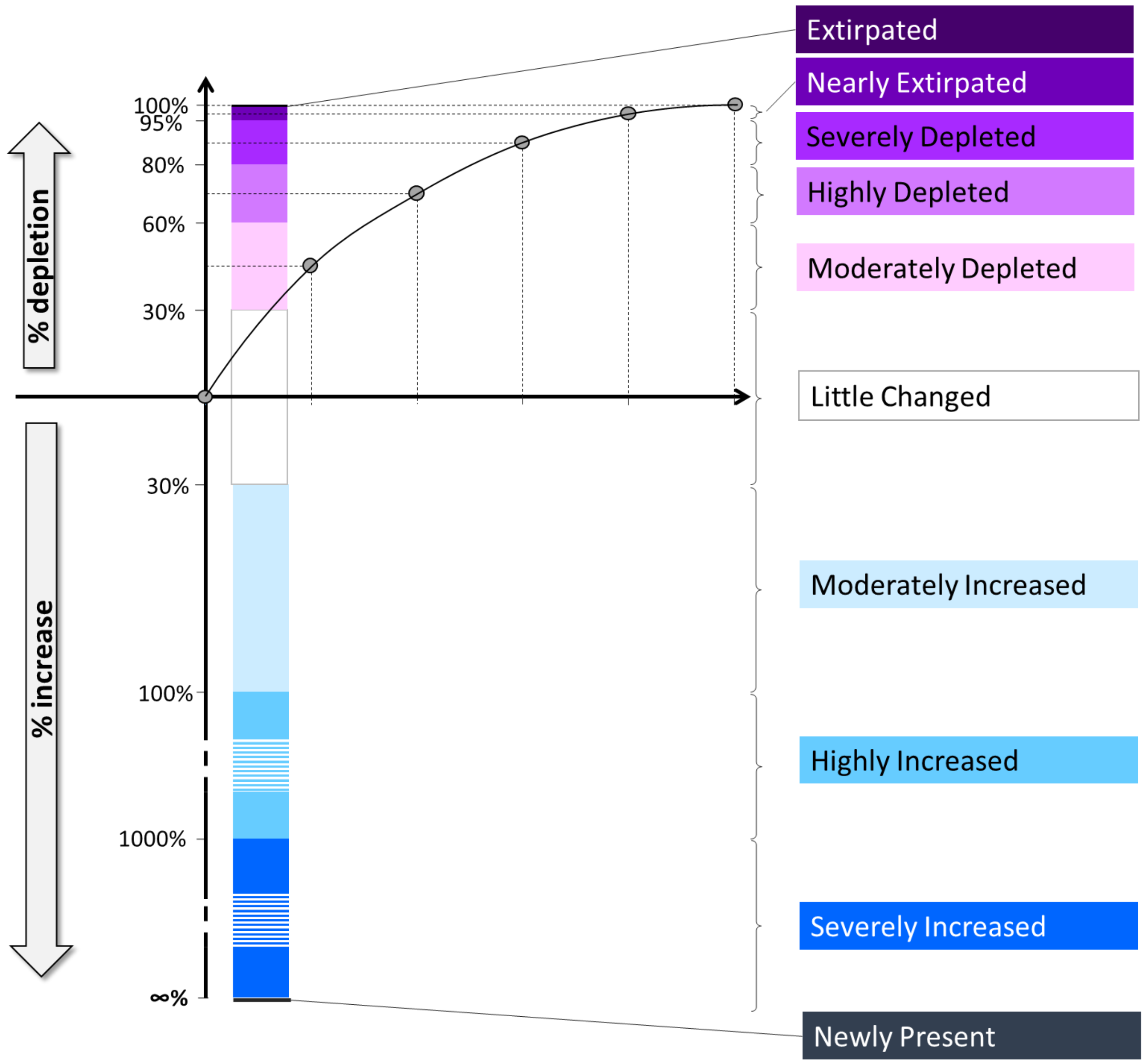

Figure S2. Rationale for selection of thresholds in the depletion categories: classes become narrower are they approach Extirpated status (100% depletion; horizontal dashed lines and gray circles indicate the midpoint in each category of depletion to illustrate this effect).

Examples of preliminary EPOCH assessments

Table S1. Examples of preliminary EPOCH assessments, some at the level of whole species, other at the level of (infra-specific) subpopulations. This table provides additional detail to examples mentioned in the main text (including in Figure 1) as well as others, for further context. These examples are intended to illustrate of how different types of data can be applied to the proposed classification system, rather than presenting definitive EPOCH assessments (i.e., making the best use of all the available information) for the species or subpopulations considered.

Species	**Assessment unit**	**EPOCH status (preliminary)**	**Justification**
Black musselcracker *Cymatoceps nasutus*	Whole species	**Moderately Depleted** ([30%, 60%[decline). Baseline: ca. 1960.	The species, endemic to the coasts of South Africa, was classified in 2009 as Vulnerable in the IUCN Red List of Threatened Species, based on criterion A2bd (i.e., observed, estimated, inferred or suspected population size reduction of at least 30% over the last three generations, but less than 50% given that species was not classified as Endangered). According to the documentation underpinning the Red List assessment, "targeted commercial effort data indicate that CPUE [Catch Per Unit Effort] and catch declined significantly from the mid-1980s to the early 2000s and are indicative of a population decline of over 30% within three generation lengths (48 years)" [10]. This translates directly into a Moderately Depleted status for a baseline of ca. 1960 (48 years prior to the 2009 Red List assessment).
Gulf grouper *Mycteroperca jordani*	Whole species	**Severely Depleted** ([80%, 95%[decline). Also plausible: **Nearly Extirpated** ([95%, 100%[	This species, endemic to coasts of Baja California and Gulf of California, is taken by recreational and small-scale commercial fisheries throughout its range. Sáenz-Arroyo and colleagues reviewed old grey literature (e.g., fishing guides, fisheries reports), historical naturalists' observations and undertook a systematic collection of fisher's anecdotes to understand the timeline and intensity of population decline [11]. They found consistent anecdotal records that the species was considered common/abundant in the 1930s-1950s, in contrast with current perceptions that it is "naturally rare". Memories of fishers about their best fishing days (from great catches of up to 25 fish in a

		decline). Baseline: ca. 1940.	day in the 1940s and 1950s, to one or two by the 1990s) suggest at least a 10-fold reduction in abundance. Piecing together all their evidence, the authors concluded that this population declined steeply in the 1970s, and that current population size is only a few percent (and perhaps as low as 1%) of the numbers present in the 1940s [11]. Given the uncertainty associated with historical anecdotes, it is particularly important to err on the side of caution in this case (i.e., underestimating rather than overestimating population change). Based on this, we classify this species as Severely Depleted in relation to a 1940s baseline, while recognising that Nearly Extirpated is plausible too.
Wandering albatross *Diomedea exulans*	Subpopulation of Bird Island, South Georgia	**Highly Depleted** ([60%, 80%[decline). Baseline: 1962.	This subpopulation has been monitored since 1962, with direct annual censuses since 1972. The number of breeding pairs declined from 1554-1922 (mean 1714) pairs in 1962-1964, to 772 pairs in 2014/15, corresponding to a decline of about 74%, attributed mainly to decreased adult survival as a result of longline fisheries [12]. This subpopulation is thus classified as Highly Depleted in 2015 in relation to a 1962 baseline.
Kakapo *Strigops habroptilus*	Subpopulation of the North Island and the South Island of New Zealand	**Extirpated** (100% decline). Baseline: ca. 1200.	Kakapo formerly occurred throughout North and South Islands [13]. Decline started with the arrival of Polynesians (ca. 1200 AD), likely as a result of habitat transformation and predation by humans, domestic dogs (*Canis familiaris*), and Polynesian rats (*Rattus exulans*). The arrival of Europeans in the late 18th century brought further habitat loss and the introduction of other predator species, including feral cats (*Felis catus*), ship rats (*R. rattus*) and – most damagingly – stoats (*Mustela ermine*). The species became extinct in the North Island in the early 20th century (last record: 1927) but remained in relatively high abundances in Fiordland, in south-western South Island. By the 1970s, the Fiordland subpopulation had been reduced to a few aged males, the last three of which were transferred to offshore islands in 1987 [14]. The subpopulation of kakapo on North Island and South Island is thus considered Extirpated in relation to a pre-Polynesian (1200) baseline.

	Subpopulation of Stewart Island, New Zealand	**Extirpated** (100% decline). Baseline: 1970.	It is not clear if the kakapo subpopulation on Stewart Island was native or human-aided (by either Maori or Europeans). Indeed, no fossil remains have been found, and the very high genetic similarity of all Stewart Island kakapo now alive suggests a recent subpopulation from a few founders [14]. In 1977, a small subpopulation of about 100-200 birds was discovered on Stewart Island, rapidly declining through cat predation. This prompted the transferral of all remaining birds (62 in total) to offshore islands. The last record in Stewart Island is of a female found and transferred to Codfish Island/Whenua Hou in 1997 [14]. This subpopulation is thus considered Extirpated in relation to a 1970 baseline (a date at which it was known to be present).
	Subpopulation of Codfish Island/Whenua Hou, Anchor Island, Little Barrier Island/ Hauturu-o-Toi, New Zealand	**Newly Present** (∞% increase). Baseline: 1980.	There are no ancient records of kakapo in Codfish Island/Whenua Hou, Anchor Island, or Little Barrier Island/Hauturu-o-Toi and the species is thus believed not to have been historically present there [13]. Refuge subpopulations were established in these islands (and – unsuccessfully – in others) through conservation translocations, mainly of birds from Stewart Island, from 1987 onwards. These islands became predator-free subsequent to the successful eradication of multiple invasive populations. In 2018, there were 149 adult kakapo in these islands, mostly in Codfish Island/Whenua Hou [15]. As these islands are presumed to be outside the native range for this species, this subpopulation is classified as Newly Present in relation to a 1980 (pre-translocation) baseline.
Great-tailed grackle *Quiscalus mexicanus*	Subpopulation of the United States	**Severely Increased** ([1000%, ∞%[increase). Baseline: 1880.	Wehtje reviewed published records, museum specimens, egg collections and field surveys to document the expansion of the great-tailed grackle in the United States between 1880 (when it was only found in southernmost Texas) to 2002 (when it bred in 20 States), estimating that in this period the subpopulation's range expanded from c. 64,000 km2 to more than 3,561,000 km2, corresponding to an increase of 5530% [16]. This expansion is attributed to the species' capacity to readily exploit human-modified habitats, and has also been accompanied by a modification in

			migratory behaviour: from mainly a breeding visitor to southern Texas in 1880 to resident in 10 States by 2002 [16]. This subpopulation is thus classified as Severely Increased.
Common starling *Sturnus vulgaris*	Whole species	**Moderately Increased** ([30%,100%[increase). Baseline: 1500.	Common starlings are native to the Palearctic region, with a wide distribution including all of Europe, western Asia and Northern Africa. They were introduced in multiple other parts of the world and have established (and still expanding) populations in North America, Central America, the Caribbean, South Africa, Australia, New Zealand, Polynesia and Argentina. With migratory populations in the native range and in North America. The overall native range (including resident, breeding, and non-breeding) occupies 21.8 million km2, whereas the introduced range occupies 18.5 km2, thus an 85% expansion in the area occupied by this species [17]. It is thus classified as Moderately Increased, in relation to a 1500 baseline (corresponding to the European maritime expansion).
Red fox *Vulpes vulpes*	Subpopulation of Great Britain	**Highly Increased** ([100%,1000%[increase). Baseline: Białowieża forests (as surrogates for a Mesolithic baseline).	The Mesolithic red fox population in Great Britain was estimated at ca. 73,000 individuals, calculated by combining estimates of habitat extent during the Mesolithic based on pollen cores, with recent densities of foxes in relatively intact forest habitats in Białowieża National Park in Poland [18]. In contrast, the 1995 population size was estimated at ca. 240,000 individuals, based on a similar approach applied to contemporary habitat cover and observed densities in Britain [19]. This translates into an estimated increase of ca. 330% in population size, mainly attributable to habitat conversion to more favourable (more open) habitats and to mesopredator release (extinction of wolves and bears) [18]. This subpopulation is therefore classified as Highly Increased.
Red squirrel *Sciurus vulgaris*	Subpopulation of Great Britain	**Nearly Extirpated** ([95%, 100%[decline). Baseline: Białowieża forests	The Mesolithic subpopulation of red squirrels in Britain was estimated at ca. 12 million individuals, calculated by combining estimates of habitat extent during the Mesolithic based on pollen cores, with recent densities of red squirrel in high quality habitats in Great Britain [18]. The 1995 population size was estimated at ca. 160,000 individuals based on a similar approach applied

		(as surrogates for a Mesolithic baseline).	to contemporary habitat cover [19]. This translates into an estimated population decline of ca. 99%, mainly attributable to habitat loss (deforestation), and therefore to a Nearly Extirpated status for this subpopulation.
Gray whale *Eschrichtius robustus*	Eastern North Pacific subpopulation	**Little Changed** (]30% increase, 30% decline[). Baseline: ca.1800 AD.	This subpopulation was exploited by aboriginal people since pre-historical times [20,21], and it was subject to commercial whaling from the mid-1800s to the early 1900s [22]. It had collapsed by the late 1800s, but has strongly recovered since [22]. It seems to have broadly stabilised since the mid-1980s, consistent with being close to carrying capacity [23]. A recent (2015/16) survey estimated the current population size at 26,960 individuals (95% confidence interval 24,420-29,830; Durban *et al*. 2017 in [22]), close to an estimate of carrying capacity of 25,808 (19,752-49,639) individuals from a model fitted to recent population trends [24]. The historical (1600) population size was estimated at 21,200 (18,700-25,500) individuals, based on a population model applied to catch records and recent population estimates [25]. Population estimates based on genetic diversity suggest a much higher pre-whaling population size of ca. 100,000 individuals for the entire North Pacific [26,27], but are difficult to reconcile with the known record of commercial whaling and with the recent stabilisation in population size [28,29]. Overall, we consider it most likely that this subpopulation is Little Changed in relation to a 1800 baseline prior to commercial whaling.
	North Atlantic subpopulation	**Extirpated** (100% decline). Baseline: ca. 1 AD.	Gray whales no longer occur in the North Atlantic, but their past presence up to the mid-1700s is attested by a small number of bone records [30–33] and an even smaller number of historical records [34,35]. A single individual seen in the Mediterranean Sea in 2010 was presumably a vagrant from the North Pacific [36]. The paucity of records has raised the possibility that gray whales were naturally rare in the Atlantic, and could thus have disappeared naturally [37]. However, the few historical records clearly present it as an exploited species, and the timeline of its disappearance coincides with a period of intensive commercial coastal whaling (mainly of right whales) [38] that plausibly could have led to the demise of gray whales in the North Atlantic. We

			thus consider this subpopulation Extirpated. The baseline is arbitrarily set to year 1 AD, a time at which the species presumably was present on both sides of the North Atlantic [32,33].
South Asian River Dolphin *Platanista gangetica*	Indus subpopulation (i.e., *P. g. ssp. minor*)	**Moderately Depleted** ([30%, 60%[decline). Also plausible: **Highly Depleted** ([60%, 80%[decline). Baseline: ca. 1870.	The Indus River system has been fragmented and transformed in the past 150 years through the construction of dams and the extraction of water for agriculture. In addition, Indus river dolphins were widely hunted in Pakistan until the 1970s [39]. Using as baseline a detailed distribution map for this subpopulation based on 1870s records, the historical linear extent of the subspecies range was estimated at about 3,500 km [40]. In contrast, the current linear extent of occurrence is approximately 1000 km, which corresponds to 71% of the original linear range size [39,41]. However, about 99% of the Indus river dolphin population now occurs in only 690 km of river, which corresponds to an almost 80% reduction in effective linear range since the 1870s [39,41]. The subpopulation was classified as Endangered in the IUCN Red List (in 2012) based on criterion A2, for an inferred and suspected reduction of > 50% in population size since 1944 (three generations prior to the assessment year) [42]. The current population size was estimated in 2015 at ca. 1450 individuals (ranging from 1200 to 1750, depending on the survey) [39]. Using reduction in linear extent as a surrogate to reduction in population size may lead to an overestimate of population decline, as the tributaries and upper portions of the Indus mainsteam from which the species has disappeared likely had lower densities [39]. To err on the side of underestimating change, we classify this subpopulation as Moderately Depleted, in relation to a 1879 baseline. However, it is possible that the subpopulation is Highly Depleted.
North Atlantic Right Whale *Eubalaena glacialis*	Western North Atlantic subpopulation	**Severely Depleted** ([80%, 95%[decline). Baseline: pre-whaling densities of N. Pacific right whale (*E. japonica*) as surrogate for pre-	Commercial whaling of this subpopulation started ca. 1530 by Basque whalers in the Strait of Belle Isle (Canada) region, by Basque whalers [38] (who focused on bowhead whales [43]), and continued along the eastern United States shores, peaking between the 1690s and 1730 [38]. It was considered commercially extinct by 1750 [44], but its exploitation continued into the early 1900s [38], before it became legally protected in the 1930s. The population was recovering slowly between 1990 and 2010, but is now declining again because of entanglement in fishing gear and ship strikes [45]. The total population size in 2015 was estimated at 468 animals (95% interval: 444-

		whaling densities, ca. 1500.	471) [46]. Monsarrat and colleagues [47] estimated the pre-whaling population size by extrapolating from the ecologically similar sister species North Pacific Right Whale (*E. japonica*): they built a statistical model of the relationship between right whale relative density and environmental conditions during the summer feeding season from a spatially explicit data set on historical catches of the North Pacific species, and then projected into the eastern North Atlantic to obtain an estimated carrying capacity of 3,906 to 9,181 North Atlantic right whales. Taking this as an estimate of the pre-whaling (pre-1500) population size, this translated into a Severely Depleted status.
Omura's whale *Balaenoptera omurai*	Whole species	**Undetermined** (> 0% decline plausible, but unknown if ≥ 30%)	This species was only described in 2003, having been formerly regarded as a small form of Bryde's whale (*B. brydei/edeni*) [48]. The relatively few confirmed observations indicate that it is widely distributed in primarily tropical and warm-temperate locations, mainly (but not exclusively) in coastal and neritic areas, perhaps occurring as relatively small, localised subpopulations [49]. There is no reliable estimate of population size [50]. It may have been taken in the past as part of commercial whaling operations, especially in southwestern Japan [50], and its primarily coastal and shallow water distribution give it a relatively high probability of entanglement and bycatch in local fisheries, ship strikes, and effects of coastal development and coastal industry [49]. However, the extent to which such factors might have affected population size is unknown, and accordingly the species is classified in the IUCN Red List as Data Deficient [50]. For the same reasons, we classify it here as Undetermined.

EPOCH assessment of subpopulations of bowhead whale, *Balaena mysticetus*

Introduction

Bowheads are massive whales (females up to 20 m; males up to 18 m; up to 100 tonnes), and the species with the longest baleen (up to 5 m in length). Endemic to Arctic and sub-Arctic waters, they are closely associated with pack ice, where they feed mainly on copepods and euphausiids. They have a circumpolar distribution, occurring in the North Atlantic Ocean (north-eastern Canada, West Greenland, East Greenland, Svalbard, Barents and Kara seas) and North Pacific Ocean (Bering-Chukchi-Beaufort seas, and Sea of Okhotsk), with distribution and movements that follow seasonal changes in sea-ice cover [51].

Bowhead exploitation started in ancient times, going back at least 2000 years, through aboriginal whaling in Alaska, north-eastern Siberia, the Canadian Arctic, and Greenland [52,53]. Because of their high oil yields and valuable baleen, bowheads were among the most prized targets of industrial whaling from the 16th to the early 20th centuries. Their large-scale exploitation started with Basque whalers in the Strait of Belle Isle and the Gulf of Saint Lawrence about 1540, subsequently joined by other nations (Dutch, English, German, American) as it expanded into the seas around Svalbard in the early 1600s, into the Davis Strait region by 1700 and into Hudson Bay by 1860 [54–56]. In the North Pacific, whaling was dominated by Americans, starting in the Bering Sea in 1848, and in the Okhotsk Sea around 1855 [57]. Even after 1860, when petroleum began to steadily replace whale oil, the high value of baleen sustained the artic whaling industry [55]. All subpopulations had been seriously depleted long before the 1930s, when commercial whaling of bowheads was prohibited under international conventions [58]. Some of the subpopulations have recovered substantially since, and the species is currently classified as Least Concern in the IUCN Red List of Threatened Species [58].

We considered four range sub-divisions, i.e. subpopulations, based on the different stocks recognised by the Scientific Committee of the International Whaling Commission, differences in histories of exploitation and trajectories of recovery (Figure S3).

Figure S3. EPOCH assessments of four subpopulations of bowhead whale (*Balaena mysticetus*): Bering–Chukchi–Beaufort Seas (BCB, Little Changed, 1800 baseline); Okhotsk Sea (OS, Severely Depleted, 1800 baseline); East Greenland–Svalbard–Barents Sea (EGSB, Nearly Extirpated, 1600 baseline); and Eastern Canada–West Greenland (ECWG, Moderately Depleted, 1500 baseline). We map separately the region of the Strait of Belle Isle and Gulf of St. Lawrence (BISL), which is part of ECWG, as it is no longer occupied (thus mapped as Extirpated).

Bering–Chukchi–Beaufort Seas subpopulation (BCB)

Whales in this subpopulation spend summer north of the Bering Strait, from Chaunskaya Guba (Russian Federation) in the western Chukchi Sea through the eastern Chukchi and Beaufort Seas and east to Amundsen Gulf and Viscount Melville Sound (Canada). Most of the whales appear to migrate into the Bering Sea in winter. In the 19th century, substantial catches were also taken in summer in the Bering Sea, when climatic conditions were different from today's [58].

This subpopulation has been exploited for millennia, although it is difficult to establish when active whaling started. The earliest evidence of bowhead whaling comes from the Bering Strait region, about 2000 years ago, with the Okvik and Old Bering Sea cultures. After 900 AD, the Thule culture expanded from the Bering Strait area west to Siberia and north and east across arctic Alaska and Canada as far as Greenland within just a few hundred years. The Thule people were efficient and specialised whalers, mainly targeting immature individuals. They reached the height of their influence between 1100-1300 AD, and had already declined (possibly because of climate change) by the time the first American commercial whalers entered the region (see [53] for a review). Although it is difficult to estimate how many bowheads were taken pre-contact, the removals are not believed to have depleted the subpopulation [53].

Commercial whaling on this subpopulation began in 1848 in the Bering Strait region and expanded rapidly. Dominated by Americans, the hunt also included ships from France, Germany, Hawaii and Australia. By 1854, population size had already declined to the extent that whalers abandoned the Bering Strait whaling for the Okhotsk Sea, before returning back again in 1858 when the latter had been decimated. For the following half-century, whalers continued to pursue bowheads farther into the ice and earlier in the season, at considerable risk. In the 1880s, even though the price of whale oil had fallen due to the development of the petroleum industry, the sharp increase in the price of baleen and the development of steam power continued to propel the industry. By 1908 the baleen market had collapsed, and the end of commercial bowhead whaling came in 1921 (see [57] for more details).

The pre-commercial whaling abundance of the Bering–Chukchi–Beaufort subpopulation of bowheads has been estimated at 10,400 to 23,000 [59], 9,500 to 28,500 [60] and 13,000 to 24,000 [61]. The minimum population size is believed to have been reached in around 1914, with only about 1000 individuals remaining [59].

The subpopulation has been recovering steadily since the end of commercial whaling, notwithstanding low levels of legal subsistence aboriginal whaling [53]. The current population size was estimated at 16,900 (15,700-18,900) in 2011 from shore/ice-based counts [62] or 19,000 (12,400-28,500) from photo-identification capture-recapture [63]. Based on these values, the subpopulation is classified as Little Changed (<30% depleted), based on a 1800 baseline (prior to the onset of commercial whaling).

Okhotsk Sea subpopulation (OS)

The Okhotsk Sea subpopulation occurs in the northern and western Sea of Okhotsk (from Shantarskiye Zaliv east to Zaliv Shelikova, Gizhiginskaya Guba, and Penzhinskaya Guba) [58] and it appears to be genetically and geographically isolated [64].

Maritime Koryaks exploited bowheads in the north of the Sea of Okhotsk in the pre- and early-contact periods [53]. Commercial exploitation started in 1846 or 1847 (mainly by Americans; also French and British whalers), becoming particularly intense in 1855 to 1857, during which over 6000 whales were taken and the subpopulation became substantially depleted. The region continued to be visited sporadically by whalers up to 1913, including undetermined catches by Russian whalers. Incomplete records and confusion with North Pacific right whales make it difficult to estimate with certainty how many bowhead whales were taken, and thus the original population size. Estimates for the latter range from 3000 to 20,000 depending on assumptions about the past catches [65].

This subpopulation does not seem to have recovered despite formal protection in the 1930s and indeed it seems to be currently declining. It is classified as Endangered in the IUCN Red List given evidence that it contains fewer than 250 mature individuals [66]. Indeed, total current population size has been estimated at 388 ± 108 [67] or at 218 (coefficient of variation 0.22) [68]. Based on the relationship between these values and estimated pre-whaling population size, the subpopulation is at best Severely Depleted (80% to 95% depleted) but possibly Nearly Extirpated (depleted by more than 95%), based on a 1800 baseline (prior to the onset of commercial whaling). To err on the side of underestimating depletion, we classify it here as Severely Depleted.

East Greenland–Svalbard–Barents Sea subpopulation (EGSB)

The East Greenland–Svalbard–Barents Sea subpopulation extends from the east coast of Greenland eastwards across the Greenland Sea, the Barents Sea, and the Kara Sea to Severnaya Zemlya, and southwards at least occasionally to northern Iceland, Jan Mayen and the coast of Finnmark [69].

Aboriginal bowhead whaling in eastern Greenland apparently started with the arrival of the Thule culture in the 13th century, flourished in the 16th and 17th centuries, and disappeared with the depletion of bowhead stocks by European whalers [53].

Commercial whaling started in 1611 in Svalbard by an English ship staffed with Basque whalers, soon joined by Dutch, Basque and Danish whalers. This fishery was initially coastal ("bay whaling"), off the coasts of Svalbard and Jan Mayen, peaking between 1620 and 1640. As whales became scarcer around these islands, whalers abandoned the shore stations and turned westwards, through pelagic whaling along the edge of the sea ice in the Greenland Sea. Dutch and German voyages declined after 1770 and ended by 1830; English and Scottish voyages peaked in the 1810s-1820s and then declined up to 1911. In total, about 100,000 whales were taken [54–56].

The size of the East Greenland–Svalbard–Barents Sea subpopulation prior to commercial whaling is estimated to have been in the range 33,000-65,000, based on a simple population model (Allen and Keay 2006) using historical catch data from Dutch, German, and British sources compiled by de Jong (1983).

Models calibrated to historical catch data from Dutch, German, and British sources [54], were used to estimate pre-whaling population size, with different results depending on model parameters and assumptions: 23,973 individuals [59], 46,000 individuals (Hacquebord and Leinenga 1994, in [56]), or 52,500 adult whales (ranging from 33,000 to 65,000) [56]. These models assume 1000 whales remaining in 1911, but the subpopulation must have come very close to extinction, as between 1940 and 1990 only 37 confirmed sightings were reported [70]. The current population size is estimated to be in the low hundreds, with less than 250 mature whales, and so this subpopulation is considered Endangered in the IUCN Red List of Threatened Species [69].

Based on these values, we consider this subpopulation to be Nearly Extirpated (>95% depletion), based on a 1600 baseline (prior to the onset of commercial whaling).

Eastern Canada–West Greenland (ECWG), including the Strait of Belle Isle – Gulf of St. Lawrence subpopulation (BISL)

This subpopulation is currently found in Hudson Bay, Foxe Basin, Hudson Strait, Davis Strait, Baffin Bay, Gulf of Boothia, Prince Regent Inlet, and other waters of the Canadian Arctic Archipelago [58]. It also occurred historically in the Strait of Belle Isle and the Gulf of St. Lawrence [43].

Aboriginal whaling of this subpopulation developed mainly under the Thule culture, including in Hudson Bay, in Labrador and in western Greenland, then declining with the depletion of bowhead stocks by European whalers [53].

Commercial whaling started in about 1540 with Basque whalers, who targeted whales as they entered the Gulf of St. Lawrence via the Strait of Belle Isle [43]. This coastal fishery peaked in the 1560s and the 1570s, declining afterwards; it was abandoned by the 1630s as the Svalbard whaling developed [55]. In the late 17th century, Danes and Dutch started whaling in the Davis Strait, a fishery dominated by Dutch in the 18th century. British whalers dominated in the 19th century, as they expanded the whaling range across Baffin Bay, with catches peaking in the 1830s. In the 1890s, whalers extended into Hudson Bay, often engaging in long trips that required overwintering in the north; as the value of baleen exceeded that of oil, only the latter was saved. Commercial whaling of this subpopulation had largely ended by 1915 [55] but small numbers continued to be taken sporadically by and on behalf of shore-based trading companies as well as by Inuit for subsistence [71,72].

Whaling records for this subpopulation are incomplete, particularly for the early period in the Gulf of St. Lawrence and the Strait of Belle Isle. Reviewing known sources and making a set of assumptions regarding the earlier catches (e.g. assuming 90% of Basque catches were bowhead whales) Higdon estimated that 55,916–67,537 bowheads were taken from this subpopulation between 1530–1915 [73]. From this series of catch data, a recent study using deterministic discrete-time logistic population models estimated an original population size of 17,495 to 19,004 individuals (depending on the model), a current population size (in 2011) of 6,205 to 14,724, and current depletion level somewhere between 23% and 64% [71]. The subpopulation is thus assumed to be Moderately Depleted (30% to 60% depletion) although it cannot be excluded that it is Little Changed (<30% depletion) or Highly Depleted (60 to 80% depletion), based on a 1500 baseline (prior to the onset of commercial whaling).

This subpopulation is currently increasing, but it has not (yet) re-colonised the Strait of Belle Isle and Gulf of St. Lawrence (but see [74] for a few recent records of bowheads in Newfoundland and in the Gulf of Maine, well south of their Arctic range). It is not clear whether their current absence from this region reflects a range contraction after the end of the Little Ice Age or extirpation caused by whaling, or a combination of both [43]. We map for now the species as Extirpated (100% depletion) in the BISL region, although this may need revising.

Species-level EPOCH assessment

A possible first approach for assessing the bowhead whale at the species level is to measure change in overall range. As the species still occupies most of its historical range, having lost only an estimated 6%, this would result in a Little Changed classification.

A second approach consists of combining information on the historical range size of each subpopulation with category of population change. This may be the only available option if there are no estimates of total current and/or baseline population sizes, which can happen if change was inferred from measures of relative abundance (e.g., declines in encounter rates) or from qualitative information (e.g. historical records as evidence of change from common to rare). In practice, this can be done through the following steps: (i) assume that abundance was distributed uniformly across the historical range (such that relative area occupied by each subpopulation can be used as crude indicator of relative baseline population size); (ii) assume that the level of population change for each subpopulation corresponds to the mid-points of the respective category of change (e.g., if classified as Highly Depleted, i.e., 60 to 80% depletion; mid-point is 70% depletion); and then (iii) calculate the population change for the overall species as the average change across subpopulations, each subpopulation weighted by the relative fraction of the global range it corresponds to and the respective category of population change. For the values in Table S2, this results in an overall depletion level of 58% (= 0.26×0 + 0.09×0.875 + 0.33×0.975 + 0.25×0.45 + 0.06×1), corresponding to Moderately Depleted.

If, as is the case here with bowhead whales, it is possible to obtain more precise estimates of baseline and current population sizes for each subpopulation, then these should be used instead. For the values in Table S2, this corresponds to an overall depletion level of 66% (=1-28,968/84,809), hence Highly Depleted. As this latter classification is the one that makes the best use of the available information, it is the one that prevails as the EPOCH assessment for the overall species.

When combining EPOCH assessments from multiple subpopulations into an overall species-level assessment, it may not be straightforward to define what the corresponding overall baseline is. Indeed, if the species has been impacted at different time periods throughout its range, or if there are different depths of knowledge about those impacts, then it may not be possible to establish a single date that is suitable as a common baseline. In the bowhead whale case, it is tempting to define the earliest date – 1500 – as the overall baseline, as it corresponds to a date that precedes commercial whaling across the entire range. However, this corresponds to stating that for those populations for which commercial exploitation started afterwards, we are confident that there were no impacts between 1500 and the onset of commercial whaling (e.g., that exploitation by Maritime Koryaks in the Okhotsk Sea had zero effect on the population size from 1500 to 1800). In this case, given the information available to us, a more accurate definition of the baseline for the overall species is "prior to commercial whaling" rather than the specific 1500 date.

Table S2: Data underpinning the combination of infra-specific (subpopulation) EPOCH assessments of population change into an overall species EPOCH assessment. Total (baseline and current) population sizes obtained as averages across different studies. Range size obtained from the mapped polygons (Figure S3).

	Baseline population size (baseline date)	Current population size	Category of population change (range; mid-point)	Area km² (%)
Bering – Chukchi – Beaufort Seas (BCB)	18,067(1) (1800 AD)	17,950(2)	Little Changed (30% increase - 30% decline; mid-point: 0%)	2,591,581 (26%)
Okhotsk Sea (OS)	11,000(3) (1800 AD)	303(4)	Severely Depleted (80-95% decline; mid-point: 87.5%)	880,775 (9%)
East Greenland – Svalbard – Barents Sea (EGSB)	37,492(5) (1600 AD)	250(6)	Nearly Extirpated (95-100% decline; mid-point: 97.5%)	3,242,615 (33%)
Eastern Canada – West Greenland (ECWG) [including the region of the Strait of Belle Isle and Gulf of St. Lawrence (BISL)]	18,249(7) (1500 AD)	10,465(8)	Moderately Depleted (30-60% decline; mid-point: 45%) [BISL region: Extirpated (100% decline)]	3,117,240 (31%) [of which BISL = 628,892 (6%)]
Total	84,809	28,968		9,832,211

Estimates of baseline and current population size: (1) average between the midpoints of the range of estimates in [59], [60], and [61]; (2) average between midpoints of the range of estimates in [62] and [63]; (3) midpoint of the range of estimates in [65]; (4) average between estimates in [67] and [68]; average between estimates in [59], Hacquebord and Leinenga 1994 in [56] and [56]; max number of mature whales in [69]; midpoint of the range of estimates in [71]; (8) midpoint of the range of estimates in [71].

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