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LETTER

Consistent Extinction Risk Assessment under the U.S. Endangered Species Act

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Abstract

Identifying species at risk of extinction is essential for effective conservation priority-setting in the face of accelerating biodiversity loss. However, the levels of risk that lead to endangered or threatened listing decisions under the United States Endangered Species Act (ESA) are not well defined. We used a Bayesian population modeling approach to estimate levels of risk consistently for 14 marine species previously assessed under the ESA. For each species, we assessed the risks of declining below various abundance thresholds over various time horizons. We found that high risks of declining below 250 mature individuals within five generations matched well with ESA endangered status, while number of populations was useful for distinguishing between threatened and "not warranted" species. The risk assessment framework developed here could enable more consistent, predictable, and transparent ESA status assessments in the future.

Introduction

Identifying species at risk of extinction is essential for effective prioritization of conservation actions in the face of accelerating biodiversity loss (Butchart *et al*. 2010). Listing decisions depend on science-based risk assessment and policy decisions about society's willingness to tolerate risks (Doremus 1997). However, debate continues about how best to identify species at risk (e.g., Dulvy *et al*. 2004; Keith *et al*. 2015).

The United States Endangered Species Act (ESA) defines endangered species as "in danger of extinction throughout all or a significant portion of its range" and threatened species as "likely to become an endangered species within the foreseeable future . . . " (16 U.S.C. § 1532), but does not provide guidance on the levels of extinction risk that should lead to endangered or threatened determinations. The IUCN Red List of Threatened Species and Canada's Species at Risk Act use a rule-based approach to risk assessment that facilitates standardization, but does not enable integration of all available scientific information into the decision-making process. In contrast, the two agencies responsible for administering the U.S. Endangered Species Act (ESA), the U.S. Fish and Wildlife Service (USFWS) and the National Marine Fisheries Service (NMFS), generally use a weight-of-evidence approach that accounts for the complexity inherent to biological systems (Waples *et al*. 2013). Consequently, the differences in risk levels between species listed as endangered or threatened or determined not warranted for listing under the ESA are difficult to discern. Scientists have interpreted the question "*Is this species in danger of extinction?*" and summarized risks in various ways, leading to repeated calls for a more standardized approach to ESA status assessments (e.g., National Research Council 1995; DeMaster *et al*. 2004).

Species face diverse threats but ultimately become vulnerable to extinction through small population size or restricted range, or through declines in abundance, number of populations, or geographic range (Tear *et al.* 1993; Shaffer and Stein 2000; Goble 2009; Leidner and Neel 2011). We incorporated these demographic processes into a single science-based risk assessment question that integrates the small population and declining population paradigms (Gilpin and Soulé 1986; Caughley 1994): "*Is the species at risk of falling below a critically low abundance threshold or number of populations within a specified time horizon?*" We then developed a framework for consistent scientific analysis of extinction risks and used it to investigate the critical abundance thresholds, numbers of populations, and time horizons implied by past listing decisions. This retrospective approach does not require that all past decisions were correct. Rather, we propose that analysis of past listing decisions can provide a useful starting point for NMFS and USFWS to develop a more standardized approach to status assessments in the future.

The ESA defines "species" to include species, subspecies, and distinct population segments (16 U.S.C. § 1532), and we use the term "species" in this broad sense throughout. A species may comprise one or more demographically independent populations, defined here as geographically or otherwise distinct groups "isolated to such an extent that exchanges of individuals among ... populations do not substantially affect the population dynamics or extinction risk ... over a 100-year time frame" (McElhany *et al.* 2000). We use the term "population" in this sense throughout.

A population has declined to critically low abundance when Allee effects, demographic stochasticity, or genetic effects become a substantial source of risk (McElhany *et al.* 2000). Low abundance does not necessarily trigger an endangered or threatened listing under the ESA in the absence of threats (Ashe 2010). Nevertheless, allowing populations to fall below critically low abundance thresholds may lead to a sharp reduction in the chances of recovery while the costs of recovery efforts increase. Assessing the risks of declining below a critically low abundance threshold rather than to absolute extinction also minimizes the uncertainty associated with our limited understanding of population dynamics at very low abundance (Busch *et al.* 2013). We therefore estimated the risks that populations would decline below a critically low abundance threshold.

The phrase "in danger of extinction" requires a specified time horizon because all species eventually go extinct (Mace and Lande 1991). Under the ESA, the time horizon for threatened should be longer than for endangered because the ESA describes threatened species as likely to become endangered in the foreseeable future (Waples *et al.* 2007). Endangered species urgently require strong protective measures to prevent extinction, while threatened species require pre-emptive measures to reduce the risks of becoming endangered in the foreseeable future (Doremus 1997; Bean 2009). For listing decisions to be effective, the time horizon for endangered should be sufficient to identify and implement measures to prevent extinction (de la Mare 1987). Longer time horizons might therefore be appropriate for long-lived species with low productivity levels (Musick 1999). The IUCN Red List criteria address this by using generation length to scale time horizons differently for short-lived versus long-lived species (IUCN 2001).

Species survival also depends on the number of populations and their spatial distribution in relation to the scale of perturbations (Shaffer 1987). Some species depend primarily on a single relatively resilient population (Harrison 1994), but most have evolved as metapopulations or a complex of multiple populations and may be vulnerable to extinction if reduced to just a few populations. Short-lived species, in particular may require spatially dispersed populations to mitigate broad-scale threats, environmental variation, and catastrophes (McElhany *et al.* 2000; Hilborn *et al.* 2003).

Our research objective was to identify the critically low abundance threshold and time horizons that tend to maximize the differences in risk levels between species listed as endangered versus threatened, and listed species versus those determined not warranted for listing. Greater differences in risk levels reduce the potential for misclassification given uncertain risk estimates. We did not seek to identify precise risk thresholds because percent risk thresholds are more sensitive to changes in data, assumptions, and methods than the more disparate abundance thresholds and time horizons considered here (see Beissinger and Westphal 1998; Connors *et al.* 2014 for discussion of variation in risk estimates).

We used a Bayesian state-space model to estimate risks consistently across case study species, based on projections of recent population dynamics derived from population count or index data. We did not include species that primarily face evolving threats that would require a customized population viability analysis, undermining our goal of applying consistent analytical methods across species. Similar methods have been used in previous simulation analyses (Regan *et al.* 2013), demonstrating that they are broadly applicable to terrestrial, freshwater, and marine species assessed under the ESA.

The set of potential case study species was constrained by the availability of population count or index data at the time of the listing decision. NMFS has published status reviews that provide a detailed record of the data used to support listing decisions for most marine and anadromous species assessed since 1990. We therefore reviewed published status reviews for all NMFS species assessed

Table 1 Case study species. Estimated abundance and trend are for ESA species at the time of the listing decision in the year indicated

Species	ESA status	Abundance[a]	Number of populations	Trend	Generation length (years)
Black abalone (*Haliotis cracherodii* Leach, 1814)	EN, 2009	<Density threshold	Many	Declining	14
Southern Resident killer whale (*Orcinus orca* Linnaeus, 1758)	EN, 2005	≤41 mature individuals	1	Fluctuating	20
Fiji petrel (*Pseudobulweria macgillivrayi* Gray, 1860)	EN, 2009	<50 mature individuals	1	Declining	15
Short-tailed albatross (*Phoebastria albatrus* Pallas, 1769)	EN, 2000	~600 mature individuals	~1	Increasing	24
South Pacific loggerhead (*Caretta caretta* Linnaeus, 1758)	EN, 2011	>1,000 mature females	3?	Declining	50
Gulf of Maine Atlantic salmon (*Salmo salar* Linnaeus, 1758)	EN, 2009	<1,500 annual adult returns	~1	Declining	4
Western Steller sea lion (*Eumetopias jubatus* Schreber, 1776)	EN, 1997	~12,000 mature females at index rookeries	Many	Declining	10
Ozette Lake sockeye (*Oncorhynchus nerka* Walbaum, 1792)	TH, 1999	~700 average annual escapement	1	Declining	4
Upper Columbia River steelhead (*Oncorhynchus mykiss* Walbaum, 1792)	TH, 2006	~12,900 average annual escapement	3	Fluctuating	5
Snake River spring/summer Chinook salmon (*Oncorhynchus tshawytscha* Walbaum, 1792)	TH, 1992	~10,000 average annual escapement	Many	Declining	5
Puget Sound steelhead (*Oncorhynchus mykiss* Walbaum, 1792)	TH, 2007	>10,000 average annual escapement	Many	Mixed	5
Northwest Atlantic loggerhead (*Caretta caretta* Linnaeus, 1758)	TH, 2011	~30,000 mature females	≥5?	Stable	50
Quinault Lake sockeye (*Oncorhynchus nerka* Walbaum, 1792)	NW, 1998	>30,000 average annual escapement	1	Declining	4
Hawaiian Islands black-footed albatross (*Phoebastria nigripes* Audubon, 1849)	NW, 2011	>128,000 mature individuals	Many	Stable or increasing	19

[a] All populations combined.

between 1990 and 2012, together with all published status reviews for marine species that fall under USFWS' mandate. We selected 14 case study species with adequate count or index data, covering a broad taxonomic range (mammals, birds, turtles, molluscs, and fishes), diverse life-history types including short-lived and long-lived species, and a range of demographic attributes from inherently small and restricted-range populations to large widespread populations facing declines (Table 1). The three seabirds fall solely under USFWS' mandate, the two marine turtles are managed jointly by USFWS and NMFS, and the remaining nine species fall solely under NMFS' mandate.

Methods

We used a Bayesian state-space model incorporating a stochastic density-independent exponential growth model to estimate risks while accounting for uncertainties in the data, the environment, parameter estimation, and model choice (see online Supporting Information for details). We then addressed our research objective by testing several options for the critically low abundance thresholds and time horizons to investigate which combination(s) of thresholds were most consistent with past listing decisions. Where appropriate, we drew on definitions and thresholds developed for the IUCN Red List of Threatened Species (IUCN 2001) to maximize compatibility with international practice.

Critically low abundance

We tested several critically low abundance thresholds: 50, 250, and 500 mature individuals. IUCN Red List Criterion D1 is based on thresholds of 50 and 250 mature individuals for Critically Endangered and Endangered respectively (IUCN 2001), but Frankham and colleagues (2014) recently recommended increasing the 250 threshold to 500 mature individuals. Mature individuals are defined as "individuals known, estimated or inferred to be capable of reproduction" (IUCN 2001). Thus, for species such as sessile invertebrates and spawning salmon, densities must be sufficient to support successful fertilization. We estimated the risks of populations declining below these critically low abundance thresholds, as populations at critically low abundance levels or below are not expected to contribute significantly to the species' persistence until they have recovered.

Minimum number of populations

We first estimated the risks of all populations within a species declining below critically low abundance thresholds. We then expanded the risk assessment framework to assess the risks of the number of populations declining below a pre-defined minimum number. An inherently concentrated or restricted-range species would not be considered endangered or threatened under the ESA in the absence of elevated threats (Ashe 2010), but extinction risks are likely to increase as a species' population becomes more concentrated (IUCN 2014). We therefore referred to historical distributions, setting the minimum number of populations to one for species that historically comprised a single population, two for species that historically comprised two populations, and three for species that currently or historically comprised three or more populations. We were unable to explore higher values because few case study species had adequate data for more than three populations.

Time horizons

We tested two sets of time horizons: (a) fixed at 50 and 100 years, respectively for endangered and threatened following Regan *et al.* (2009); and (b) scaled at 5 and 10 generations, respectively for endangered and threatened. We defined generation length as "the average age of parents of the current cohort" following IUCN (2001) and set a minimum of 20 years and a maximum of 100 years. The maximum time horizon in ESA status reviews has frequently been set at 100 years, following Thompson (1991) and IUCN (2001).

Results

We first present results for the critically low abundance thresholds and time horizons that maximize the difference in risk levels between species listed as endangered (EN) and those listed as threatened (TH) or determined not warranted (NW). We found that time horizons scaled by generation length generally provided the widest separation between endangered and nonendangered species for all the three critically low abundance thresholds (compare left and right panels of Fig. 1). The difference in risks was generally greater for critically low abundance thresholds of 500 (12%) or 250 (10%) than 50 (3%). The main outlier was the short-tailed albatross ('d' in figure), which was recovering from near-extinction with a population size of approximately 600 mature individuals at the time of the 2000 decision. In contrast, none of the critically low abundance thresholds led to consistently higher risks for endangered species when the time horizon was fixed in years (Fig. 1, right panel). When the time horizon was changed from five generations to 50 years, long-lived species such as the South Pacific loggerhead (EN) ('e' in figures) were evaluated over shorter time frames, whereas short-lived species such as the Ozette Lake sockeye (TH) and Snake River spring/summer Chinook salmon (TH) ('h' and 'j' in figures) were evaluated over longer time frames, leading to overlapping risk levels.

We next present results for the distinction between species listed as endangered or threatened and those determined not warranted. We found considerable overlap in the risks faced by threatened and not warranted species for all three critically low abundance thresholds, regardless of whether the time horizon was set at 10 generations or 100 years (Fig. 2). However, when we expanded our risk assessment to include the risks of declining below a minimum number of populations, the distinction between threatened and not warranted species became clearer (Fig. 3). Risks increased substantially for species with broad historical distributions that have become, or are at risk of becoming, more geographically concentrated, including the short-tailed albatross (EN), the Snake River spring/summer Chinook salmon (TH), and the Northwest Atlantic loggerhead (TH) ('d', 'j', and 'l' in figures). Consequently, risks were consistently higher for threatened species than not warranted species when we included a threshold for minimum number of populations, with a critically low abundance threshold of 250 or 500 mature individuals, and set the time horizon to 10 generations (left panel of Fig. 3). However, the maximum difference in risks between threatened and not warranted species was still small compared to the maximum difference between endangered and threatened species (compare Figs 1 and 3).

When analyzed together, results for the distinction between endangered and nonendangered species and between listed and not listed species indicate that the combination of a critically low abundance threshold of 500 mature individuals, time horizons scaled by generation length, and a minimum number of populations enables classification of all case study species consistent with the actual listing decision. A critically low abundance threshold of 250 mature individuals performs similarly, except for the short-tailed albatross.

Discussion

Our research objective was to identify the critically low abundance threshold and time horizons that tend to

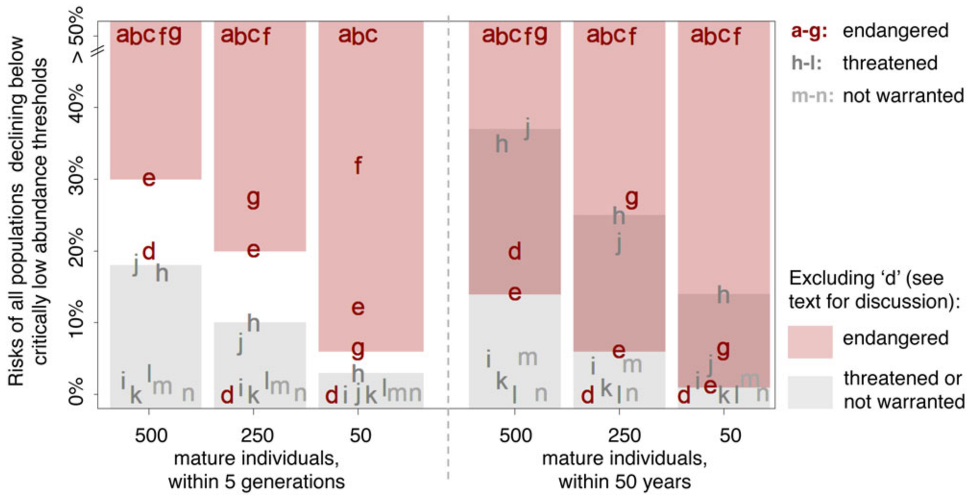

Figure 1 Species listed as endangered versus not listed as endangered: risks of all populations declining below various critically low abundance thresholds over time horizons scaled to 5 generation lengths (up to a maximum of 100 years) or fixed at 50 years. Rose color shading indicates the range of risk estimates for species listed as endangered, excluding the short-tailed albatross (d, see text for discussion); gray shading indicates the range of risk estimates for species listed as threatened or determined not warranted; overlapping shading indicates overlapping risk estimates. All analyses are based on the data available at the time of the ESA listing decision in the year indicated in Table 1 and do not necessarily reflect the species' current status. Species codes are: (a) black abalone; (b) Fiji petrel; (c) Southern Resident killer whale; (d) short-tailed albatross; (e) South Pacific loggerhead; (f) Gulf of Maine Atlantic salmon; (g) western Steller sea lion; (h) Ozette Lake sockeye; (i) Upper Columbia River steelhead; (j) Snake River spring/summer Chinook salmon; (k) Puget Sound steelhead; (l) Northwest Atlantic loggerhead; (m) Quinault Lake sockeye; and (n) black-footed albatross.

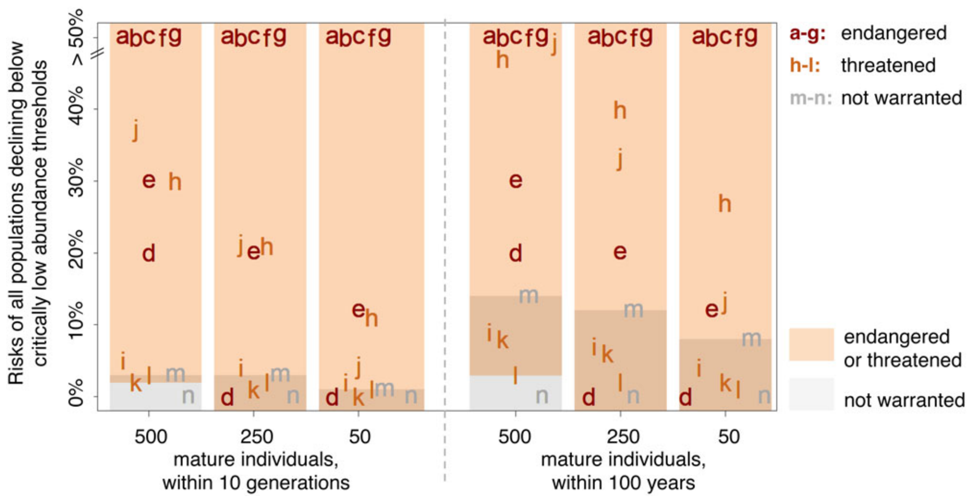

Figure 2 Species listed as endangered or threatened versus determined not warranted for listing: risks of all populations declining below various critically low abundance thresholds over time horizons scaled to 10 generation lengths (up to a maximum of 100 years) or fixed at 100 years. Peach color shading indicates the range of risk estimates for species listed as endangered or threatened; gray shading indicates the range of risk estimates for species determined not warranted; overlapping shading indicates overlapping risk estimates.

maximize the differences in risk levels between listed as endangered versus threatened and listed versus determined not warranted. Past reviews of ESA listing decisions have found that no single criterion was able to distinguish between endangered, threatened, and not warranted species (Easter-Pilcher 1996). We addressed this issue by considering various combinations of abundance, number of populations, and rates of decline.

Abundance thresholds have been used in various ESA status reviews, but definitions and magnitudes have ranged widely (Wilcove *et al*. 1993). Our analysis of 14 marine and anadromous case study species indicated

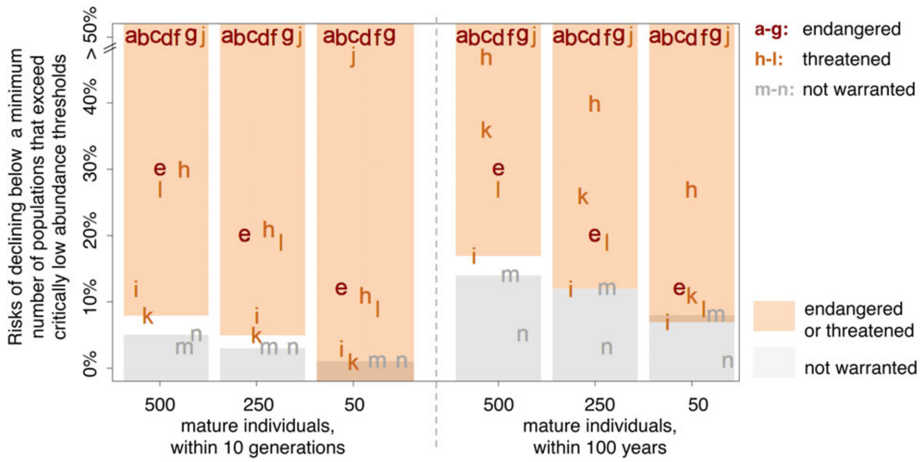

Figure 3 Species listed as endangered or threatened versus determined not warranted for listing: risks of declining below a minimum number of populations that exceed various critically low abundance thresholds over time horizons scaled to 10 generation lengths (up to a maximum of 100 years) or fixed at 100 years. Peach color shading indicates the range of risk estimates for species listed as endangered or threatened; gray shading indicates the range of risk estimates for species determined not warranted; overlapping shading indicates overlapping risk estimates.

that species that have fallen below 250 mature individuals have generally been listed as endangered. To assess whether this result was specific to our set of case study species, we used the IUCN Red List database to identify 17 marine and terrestrial vertebrate species that occur in the USA and are listed as Critically Endangered or Endangered under Criterion D1 because they have a population size less than 250 mature individuals. All are also listed as endangered under the ESA with the exception of two species currently under review (Table 2). For our 14 case study species, the difference in risk levels between listed and not warranted species and between endangered and threatened species was greater when the critically low abundance threshold was set to 250 or 500 mature individuals, rather than 50 mature individuals (Figs 1 and 3). Nevertheless, species-specific data may point to higher or lower thresholds in some cases: the historical abundance of the Southern Resident killer whale, for example, was probably substantially fewer than 250 mature individuals (see online Supporting Information). Measures of critically low abundance may also need to be adapted for corals, plants, and other taxa for which estimates of the number of mature individuals are rarely available.

Our analysis, based on past listing decisions, also indicated support for including a minimum number of populations in the risk assessment framework for species that currently or historically comprised multiple populations. Geographic concentration was identified as a major concern for several case study species at the time of listing decisions, in particular the short-tailed albatross (see online Supporting Information). In Figure 1, the endangered short-tailed albatross (‘d’ in the figure) is almost always within the range of nonendangered species. However, when we assessed the risks of declining below a minimum number of populations (Fig. 3), the short-tailed albatross always fell in the range of listed species, consistent with the rationale for the listing decision.

The differences in risk levels between endangered, threatened, and not warranted species were greater when time horizons were scaled by generations rather than years. D’Elia and McCarthy (2010) found considerable variation in the time horizons used in ESA status reviews. Very long time horizons have been used in some status reviews (e.g., for the Southern Resident killer whale Krahn *et al*. 2004) to account for the potential for long-lived species to persist for many years at population sizes too low for successful reproduction. However, the need for long time horizons is reduced in our risk assessment framework when critically low abundance thresholds are set well above levels required for successful reproduction. Our analysis indicated that time horizons of five generations for endangered and 10 generations for threatened (up to a maximum of 100 years) are consistent with past listing decisions for marine and anadromous species.

Differences in risk levels, estimated using consistent methods, were generally greater between endangered and threatened species than between threatened and not warranted species. In most cases, case study species listed as endangered were either already at critically low abundance compared to historical levels at the time of the

Table 2 Vertebrate species that occur in the USA and are listed as Critically Endangered or Endangered on the IUCN Red List of Threatened Species under Criterion D1 because the species has fewer than 250 mature individuals. (All species are taxonomic species rather than subspecies or distinct population segments. This analysis is limited to taxonomic groups that have been comprehensively assessed for the IUCN Red List.)

Species	ESA status
Mammals	
Red wolf (*Canis rufus* Audubon & Bachman, 1851)	Endangered
North Atlantic right whale (*Eubalaena glacialis* Müller, 1776)	Endangered
North Pacific right whale (*Eubalaena japonica* Lacépède, 1818)	Endangered
Black-footed ferret (*Mustela nigripes* Audubon & Bachman, 1851)	Endangered
Birds[a]	
Ivory-billed woodpecker (*Campephilus principalis* Linnaeus, 1758)	Endangered
Whooping crane (*Grus Americana* Linnaeus, 1758)	Endangered
California condor (*Gymnogyps californianus* Shaw, 1797)	Endangered
Nukupuu (*Hemignathus lucidus* Lichtenstein, 1839)	Endangered
Poo-uli (*Melamprosops phaeosoma* Casey & Jacobi, 1974)	Endangered
Olomao (*Myadestes lanaiensis* Wilson, 1891)	Endangered
Eskimo curlew (*Numenius borealis* Forster, 1772)	Endangered
Oahu alauahio (*Paroreomyza maculata* Cabanis, 1850)	Endangered
Ou (*Psittirostra psittacea* Gmelin, 1789)	Endangered
Bermuda petrel (*Pterodroma cahow* Nichols & Mowbray, 1916)	Endangered
Jamaica petrel (*Pterodroma caribbaea* Carte, 1866)	Under review[b]
Bachman's warbler (*Vermivora bachmanii* Audubon, 1833)	Endangered
Amphibians	
West Virginia spring salamander (*Gyrinophilus subterraneus* Besharse and Holsinger, 1977)	Under review

[a]Worthen's sparrow (*Spizella wortheni* Ridgway, 1884) is regionally extinct in the United States.

[b]Jamaica petrel (*Pterodroma caribbaea*) is a recent split from *P. hasitata* (Kuhl, 1820) which is under review.

listing decision (e.g., Fiji petrel and black abalone), or had high risks of declining below these thresholds within a few generations (e.g., South Pacific loggerhead, Gulf of Maine Atlantic salmon, and western Steller sea lion). The main exception was the short-tailed albatross, which was recovering from near-extinction at the time of the 2000 decision and remained geographically concentrated compared to the historical distribution and at risk of catastrophe (see online Supporting Information). In comparison, the narrow difference in risk levels faced by some threatened and not warranted species indicates the challenges of distinguishing between these two categories. Here, we estimated risks by projecting recent population dynamics into the future to provide a consistent analysis across species. For a complete assessment, this type of analysis needs to be complemented by a thorough review of threats (as required by the ESA) and assessment of the likely effects of additional threats and mitigating factors on estimated risks (see Wainwright and Kope 1999 for example). For most of the borderline case study species, additional risks or mitigating factors contributed to the final listing decision, such as the effects of artificial propagation on the long-term productivity of fish species (e.g., Upper Columbia River steelhead, see online Supporting Information).

The IUCN Red List of Threatened Species represents the most widely used standard for identifying threatened species based on quantitative demographic criteria (Mace *et al*. 2008). While we drew on IUCN Red List definitions and thresholds, we did not apply the IUCN Red List criteria per se. ESA listing decisions differ from IUCN Red List assessments in important ways. The IUCN Red List criteria are designed to support comprehensive status assessments across broad taxonomic groups, using rule-based metrics and proxies of extinction risk to highlight species that are most likely at risk (Mace *et al*. 2008). Often, more in-depth analysis is warranted before conservation actions are taken. In contrast, ESA listing decisions lead to immediate prohibitions on various activities that might jeopardize the species. Species assessed under the ESA generally have substantive scientific data indicating that listing may be warranted, allowing for more in-depth risk analysis based on the best available science and data, as required by law.

Understanding the critical abundance thresholds, numbers of populations, and time horizons implied by past listing decisions provides a valuable basis for moving towards a more standardized approach to identifying endangered and threatened species under the ESA following formal statutory and policy review (DeMaster *et al*. 2004). In the meantime, the results of our analysis present a framework for science-based risk assessment consistent with past listing decisions and could be useful in guiding future status reviews and recovery plans. In-depth species-specific status reviews offer an opportunity to assess relevant thresholds, together with additional risks and mitigating factors. In this way, the science-based risk assessment framework developed here could enable more consistent, predictable, and transparent ESA status assessments while retaining flexibility to accommodate species-specific factors.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Appendix S1. Materials and Methods
Appendix S2. Species Accounts

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