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# Which bird species have gone extinct? A novel quantitative classification approach

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ABSTRACT

Determining whether species have gone extinct requires considering the timing and reliability of records, the timing and adequacy of surveys, and the timing, extent and intensity of threats. However, previous assessments have either applied qualitative approaches or considered only the first of these factors. We applied quantitative methods encompassing all three factors to a suite of 61 potentially or confirmed extinct species of birds. We tested six different methods, each with a range of thresholds, for assigning species to IUCN Red List Categories, and compared the results with species' current categories. We recommend that if both the probability that a species remains extant based on threats and the probability based on records and surveys fall below 0.5, it should qualify as Critically Endangered (Possibly Extinct), while if both probabilities fall below 0.1 it should qualify as Extinct. This novel approach resulted in an 80% match with the current IUCN Red List classification of species. The exceptions largely reflect species whose reclassification was pending the outcome of this work. Consequently, we recommend that nine species are reclassified on the IUCN Red List, with cryptic treehunter (*Cichlocolaptes mazarbarnetti*), Alagoas foliage-gleaner (*Philydor novaesi*) poo-uli (*Melamprosops phaeosoma*) now qualifying as Extinct. We estimate a revised total of 187 extinctions since 1500, of which 90% have been of insular species. The major drivers were invasive alien species (46%) and hunting/trapping (26%). Application of this approach in non-avian groups would increase the robustness of extinction rate estimates and species' classifications on the IUCN Red List.

## 1. Introduction

Preventing species from going extinct as a consequence of human activities is one of the ultimate objectives of nature conservation, and has been adopted as a target in the Strategic Plan on Biodiversity through the Convention on Biological Diversity (CBD, 2010). Failure—the declaration of a global species extinction—generates considerable public interest and concern (e.g. Slezak, 2016; Anon., 2017), while estimates that the rate of species extinctions is about 1000 times greater than the background rate (Pimm et al., 2014) have probably helped to elevate concerns and drive policy responses to address the current biodiversity crisis (e.g. CBD, 2010).

Documenting extinctions accurately is therefore important. The IUCN Red List of Threatened Species contains the most comprehensive and regularly updated audit of species extinctions that have taken place since 1500 (IUCN, 2017). Species are classified as Extinct if 'there is no reasonable doubt that the last individual has died' (IUCN, 2001). Determining whether this is true for a particular species is not straightforward, requiring 'exhaustive surveys in known and/or expected habitat, at appropriate times (diurnal, seasonal, annual), throughout its historical range… over a time frame appropriate to the taxon's life cycle and life form' (IUCN, 2001).

Decisions about which species to classify as Extinct were previously made in an unstructured way based on expert judgement (e.g. Collar and Andrew, 1988; Collar et al., 1994). A series of papers presenting quantitative approaches to estimating extinction probability or extinction date based on the timing of records have been published since the 1990s (e.g. Burgman et al., 1995; Solow, 1993a, 1993b, 2005; Solow and Roberts, 2003; Roberts and Solow, 2003), some of which also consider the likely reliability of records (e.g. Solow et al., 2012; Lee et al., 2015). However, such approaches can estimate high extinction probability for species with no recent records, even when this can be simply explained by a lack of recent searches. They also do not take into account whether there are threats that could have plausibly driven the

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taxon extinct. To emphasise the importance of considering these factors, Butchart et al. (2006) set out a structured (but non-quantitative) framework for assessing these factors when determining which species should qualify as Extinct. A trilogy of papers published in 2017 (Akcakaya et al., 2017; Keith et al., 2017; Thompson et al., 2017) set out complementary methods for estimating extinction probability based on (a) the intensity, extent and timing of threats to a taxon, taking into account its likely susceptibility to particular threats (Keith et al., 2017); and (b) the timing and reliability of records, and the timing, scope and adequacy of surveys, taking into account the ease of detection and identification of the taxon (Thompson et al., 2017). However, these approaches have not yet been tested on more than a handful of examples.

Data on extinctions from the IUCN Red List are used both to monitor extinction rates and to determine which species no longer warrant investment of conservation resources. However, as described by Akcakaya et al. (2017), there is a tension between these two aims: it is important to avoid declaring extinction prematurely, as this may lead to the Romeo error (by which conservationists give up on a species prematurely, presuming incorrectly that they are extinct: Collar, 1998); but failing to recognise extinctions leads to underestimates of extinction rates. Butchart et al. (2006) therefore proposed that a subset of Critically Endangered species be tagged as 'Possibly Extinct': those that are, on the balance of evidence, likely to be extinct, but for which there is a small chance that they may be extant and thus should not be listed as Extinct until adequate surveys have failed to find the species and local or unconfirmed reports have been discounted. 'Possibly Extinct in the Wild' correspondingly applies to such species known to survive in captivity. Possibly Extinct species remain the target of conservation attention and resourcing, but can be included in estimates of extinction rates. This approach was subsequently adopted by the IUCN Red List (IUCN Standards and Petitions Subcommittee, 2017), and such species are identified as 'Critically Endangered (Possibly Extinct)' (i.e. 'Possibly Extinct' is a tag applied to a subset of species categorised as Critically Endangered). Akcakaya et al. (2017) proposed that the methods of Keith et al. (2017) and Thompson et al. (2017) could be used to estimate the probability that taxa survive, and that these estimates could be used to classify species as Critically Endangered (Possibly Extinct or Possibly Extinct in the Wild) or Extinct. However, a methodology for integrating the two approaches is yet to be determined, and Akcakaya et al. (2017) recommended a process of testing and consultation to determine the thresholds of extinction probability to be used for assigning species to IUCN Red List Categories.

Here we carry out such a test, and implement the first comprehensive application of the quantitative methods described by Keith et al. (2017) and Thompson et al. (2017) for estimating the probability of extinction based on threats, records and surveys. We focus on birds as these are the best studied class of organisms, including in relation to extinctions. By comparing the results with the current classifications of species as Critically Endangered, Critically Endangered (Possibly Extinct) and Extinct on the IUCN Red List, we devise a methodology to consolidate the two quantitative approaches to estimating extinction probability, and propose thresholds for assigning species to these classes, leading to a novel approach for classifying species as extinct on the IUCN Red List. Using the revised list of known and suspected extinctions, we then review the distribution and drivers of bird extinctions.

## 2. Materials and methods

Butchart et al. (2006) examined the probability of extinction of 40 bird species that had a reasonable possibility of being extinct, including any that had not been seen for > 10 years (despite reasonable searches and/or for which there was a plausible threatening process), and any that had last been seen ≤10 years ago for which there had been a well-documented decline of a tiny population. Six of those species (Madagascar pochard (*Aythya innotata*), Beck's petrel (*Pseudobulweria becki*), silvery pigeon (*Columba argentina*), night parrot (*Geopsittacus occidentalis*), Liben (= Archer's) lark (*Heteromirafra archeri*) and Bahia tapaculo (*Scytalopus psychopompus*)) have subsequently been confirmed to be extant (BirdLife International, 2017). In addition, four (hooded seedeater ('*Sporophila melanops*'), Magdalena tinamou ('*Crypturellus saltuarius*'), Liberian greenbul ('*Phyllastrephus leucolepis*') and Bulo Burti boubou ('*Laniarius liberatus*')) have been subsequently shown to be invalid taxa (Remsen Jr. et al., 2006, Nguembock et al., 2008, Areta et al., 2016, Collinson et al., 2017, del Hoyo and Collar, 2014, 2016). 'nukupuu (*Hemignathus lucidus*) has subsequently been split into the long-extinct Oahu nukupuu (*H. lucidus*), plus Kauai nukupuu (*H. Hanapepe*) and Maui nukupuu (*H. affinis*) (del Hoyo and Collar, 2016). We re-examined the evidence for extinction for both these split taxa, plus the remaining 29 species considered by Butchart et al. (2006). Of these 31 species, one is currently listed as Extinct, 13 as Critically Endangered (Possibly Extinct or Possibly Extinct in the Wild) and 17 as Critically Endangered.

We also considered 20 additional taxa that had any reasonable possibility of being extinct, including any that had not been seen for > 10 years (despite reasonable searches and/or for which there was a plausible threatening process), and any that had last been seen ≤10 years ago for which there had been a well-documented decline of a tiny population. These comprised 11 taxa that were not described or treated at the species level until after the publication of Butchart et al. (2006), but that may have already gone extinct (New Caledonian nightjar (*Eurostopodus exul*), Guanacaste hummingbird (*Amazilia alfaroana*), New Caledonian buttonquail (*Turnix novaecaledoniae*), Sinu parakeet (*Pyrrhura subandina*), cryptic treehunter (*Cichlocolaptes mazarbarnetti*), Ua Pou monarch (*Pomarea mira*), South Island kokako (*Callaeas cinereus*), Lendu crombec (*Sylvietta chapini*), Moorea reed-warbler (*Acrocephalus longirostris*), Maui akepa (*Loxops ochraceus*) and Antioquia brush-finch (*Atlapetes blancae*)), three species that were known to survive in 2006 but that may have gone extinct subsequently (Purple-winged ground-dove (*Claravis geoffroyi*), Jerdon's courser (*Rhinoptilus bitorquatus*) and Alagoas foliage-gleaner (*Philydor novaesi*)), and six taxa presumed by Butchart et al. (2006) to survive, but that may now have gone extinct (New Caledonian owlet-nightjar (*Aegotheles savesi*), pygmy-owl (*Glaucidium mooreorum*), ivory-billed woodpecker (*Campephilus principalis*), kinglet calyptura (*Calyptura cristata*), Cozumel thrasher (*Toxostoma guttatum*) and poo-uli (*Melamprosops phaeosoma*)). [Note that concerns over recent possible loss of wild populations of Edwards's Pheasant *Lophura edwardsi* (Eames and Mahood, 2018) were published too late for inclusion in our analysis.]

Finally, we added ten randomly selected (using numbers generated from www.random.org) species classified as Extinct: Amsterdam duck (*Anas marecula*), Bonin woodpigeon (*Columba versicolor*), Rodrigues turtle-dove (*Nesoenas rodericanus*), Hodgen's waterhen (*Tribonyx hodgenorum*), laughing owl (*Sceloglaux albifacies*), Mauritius owl (*Mascarenotus sauzieri*), Guadalupe caracara (*Caracara lutosa*), Mascarene parrot (*Mascarinus mascarin*), mysterious starling (*Aplonis mavornata*) and Norfolk starling (*Aplonis fusca*). Hence we assessed 61 species in total.

For each of these 61 species, we assembled information from published literature, grey literature and personal correspondence with relevant experts on the timing, scope and severity of impacts to the species (and their susceptibility to such threats), confirmed and claimed records, and surveys undertaken. We used this information to estimate the following parameters described by Keith et al. (2017) and Thompson et al. (2017); see Table 1 for definitions and Appendix 1 for estimates. For each species, we assessed $p(local)$: the probability that the combination of threats affecting the species occurred for a sufficient duration and were sufficiently severe that they caused local extinction; and $p(spatial)$: the probability that the threats occurred over the species' entire range. For each record, we assessed $p(ci)$: the probability that the taxon was correctly identified. For each survey, we assessed ε: the proportion of the species' habitat that was surveyed within its likely entire range ($0 \leq \varepsilon \leq 1$); $p(r)$: the probability that the taxon, or recent evidence of it, would have been recorded in the survey; and $p(i)$: the probability that the taxon, or recent evidence of it, could have been reliably identified in the survey if it had been recorded. Table 1 provides definitions and explanatory notes on how the parameters were assessed. We also estimated values for ε, $p(r)$ and $p(i)$ for years in which there was no record or survey, reflecting random processes in which the taxon may be recorded serendipitously by local or visiting birdwatchers, scientists, conservationists and/or local people, without specific targeted searches, generally termed passive surveillance. For years in which there was both a survey and one or more records, we used the data on the latter, following Thompson et al. (2017). For years in which there was more than one record, or more than one survey, we used the highest probability estimates following Thompson et al. (2017).

We then used these estimates to calculate the probability that each taxon remained extant based on threats (using the methods in Keith et al., 2017 and summarised in Appendix 2) and based on records and surveys (using the methods in Thompson et al., 2017 and summarised in Appendix 2). The methodological workflow is summarised in Fig. A1.

We tested six approaches for using these results to determine which species should be listed as Critically Endangered (Possibly Extinct) and which as Extinct: (method 1) assigning the relevant category to any species for which the best estimate of *both* P(extant based on records and surveys) *and* P(extant based on threats) were less than a threshold value; (method 2) assigning the relevant category to any species for which *either* P(extant based on records and surveys) *or* P(extant based on threats) were less than a threshold value; (method 3) assigning the relevant category to any species for which the *sum* of P(extant based on records and surveys) and P(extant based on threats) was less than a threshold value; (method 4) assigning the relevant category to any species for which P(extant based on records and surveys) was less than a threshold value; (method 5) assigning the relevant category to any species for which P(extant based on threats) was less than a threshold value; and (method 6) assigning the relevant category to any species for which for which the least uncertain of P(extant based on records and surveys) and P(extant based on threats) was less than a threshold value, using the minimum and maximum values of estimates in each case (Fig. 1). For the boundary between Critically Endangered and Critically Endangered (Possibly Extinct), we tested thresholds of 0.1, 0.2, 0.3… 0.9, apart from method 3 for which we tested 0.1, 0.2, 0.3…1.5. For the boundary between Critically Endangered (Possibly Extinct) and Extinct, we tested thresholds of 0.02, 0.04, 0.06…0.18, apart from method 3 for which we tested 0.02, 0.04, 0.06…0.3.

To assess each method and threshold, we compared the resultant categorisations with the species' current IUCN Red List Categories. In each case, we calculated the rate of mismatches for the Critically Endangered (Possibly Extinct) threshold as the number of current Critically Endangered species misclassified as Critically Endangered (Possibly Extinct) or Extinct, plus the number of Critically Endangered (Possibly Extinct) or Extinct species misclassified as Critically Endangered, divided by 61 (the total number of candidates assessed), and multiplied by 100 to express as a percentage. Similarly, we calculated the rate of mismatches for the Extinct threshold as the number of current Critically Endangered and Critically Endangered (Possibly Extinct) species misclassified as Extinct, plus the number of Extinct species misclassified as Critically Endangered or Critically Endangered (Possibly Extinct), divided by 61 and expressed as a percentage.

To assess the pattern and drivers of extinctions across all known and suspected extinct bird species, we took the dates of extinction from BirdLife International (2017), assigned species to continents or islands

**Table 1**
Parameters estimated for each species, record and survey.

| Type of evidence | Parameter | Definition & notes |
|---|---|---|
| Threats | $p(local)$ | *The probability that the combination of threats affecting the species occurred for a sufficient duration and were sufficiently severe that they caused local extinction.*<br>This requires assessors to draw on the history of the impacts of threats on populations of the target taxon. A relevant historical observation, for example, would be that the taxon disappeared from an area shortly after the introduction of an invasive alien predator. It may also draw on examples where the threats have caused extirpation of ecologically similar or phylogenetically related taxa. Inferences about which taxa are 'ecologically similar or related' may be based on life history (e.g. life cycle structure, dependence on hosts, body size, diet), habitat ecology (e.g. microhabitat type, breeding sites) and/or phylogeny (Keith et al., 2017). |
| | $p(spatial)$ | *The probability that the threats occurred over the species' entire range.*<br>This requires assessors to evaluate two components: i) the likelihood that the threats (with sufficient severity and duration to have caused local extinction) operated throughout the entire range of the taxon (i.e. distribution of habitat and/or individuals, as appropriate); and ii) the certainty with which the range limits are known. Relevant considerations for the first component include whether the threats operated in such a pattern as to have caused extinction throughout the taxon's range. This may be influenced by the spatial occurrence of different threats, dispersal dynamics, migration patterns and patch dynamics, as well as species life-history traits and cultural factors that influence species susceptibility to threats. Relevant factors to consider for the second component (range limits) include taxonomic uncertainty, reliability of records and whether potential habitat outside the confirmed range has been adequately searched. These uncertainties can be incorporated into estimates of P(spatial) by setting upper and lower bounds taking into account plausible maximum and minimum extents of the species range (Keith et al., 2017). |
| Records | $p(ci)$ | *The probability that the taxon was correctly identified.*<br>This requires assessors to consider the type and quality of evidence, similarity of the individual recorded to taxa with which it could potentially be confused, circumstances of the record and the skill and experience of the recorder (Thompson et al., 2017). |
| Surveys | ε | *The proportion of the taxon's habitat that was surveyed within its likely entire range* ($0 \leq \varepsilon \leq 1$) (Thompson et al., 2017). |
| | $p(r)$ | *The probability that the taxon, or recent evidence of it, would have been recorded in the survey.*<br>This requires assessors to consider aspects of detectability, including body size, behaviour (e.g., activity and movement patterns, shyness, tendency to skulk, phenology, vocality, sociality), degree of crypsis, local abundance, and accessibility to/searchability of its habitat and microhabitat. Assessors should also consider the adequacy of the survey considering: i) its timing (seasonality, diurnality, time since disturbance); ii) its duration; iii) sampling and detection skill of the observers; iv) appropriateness of the techniques used (e.g., trap style, mist-net, sound recording, playback) and their application (e.g., height of mist-nets, location of cameras, positioning of malaise traps); and v) sampling intensity (e.g., length of transects, density of cameras) and design (e.g., sample stratification) (Thompson et al., 2017). |
| | $p(i)$ | *The probability that the taxon, or recent evidence of it, could have been reliably identified in the survey if it had been recorded.*<br>This requires assessors to consider the verifiability of the record, that is, the likelihood that the recorded taxon could be distinguished from a similar taxon (e.g., a congener) given its distinctiveness (e.g., in appearance, morphology, vocalizations, behaviour), and the identification skill of the observers. Assessors must consider all signs of recent evidence (e.g. scat, spoor, nests, owl pellets, woodpecker bark peelings, shells, etc.) and all life-stages at the time of the survey; for example, the mature life-form may be highly distinctive, but the juvenile may be extremely difficult to distinguish from similar taxa (Thompson et al., 2017). |

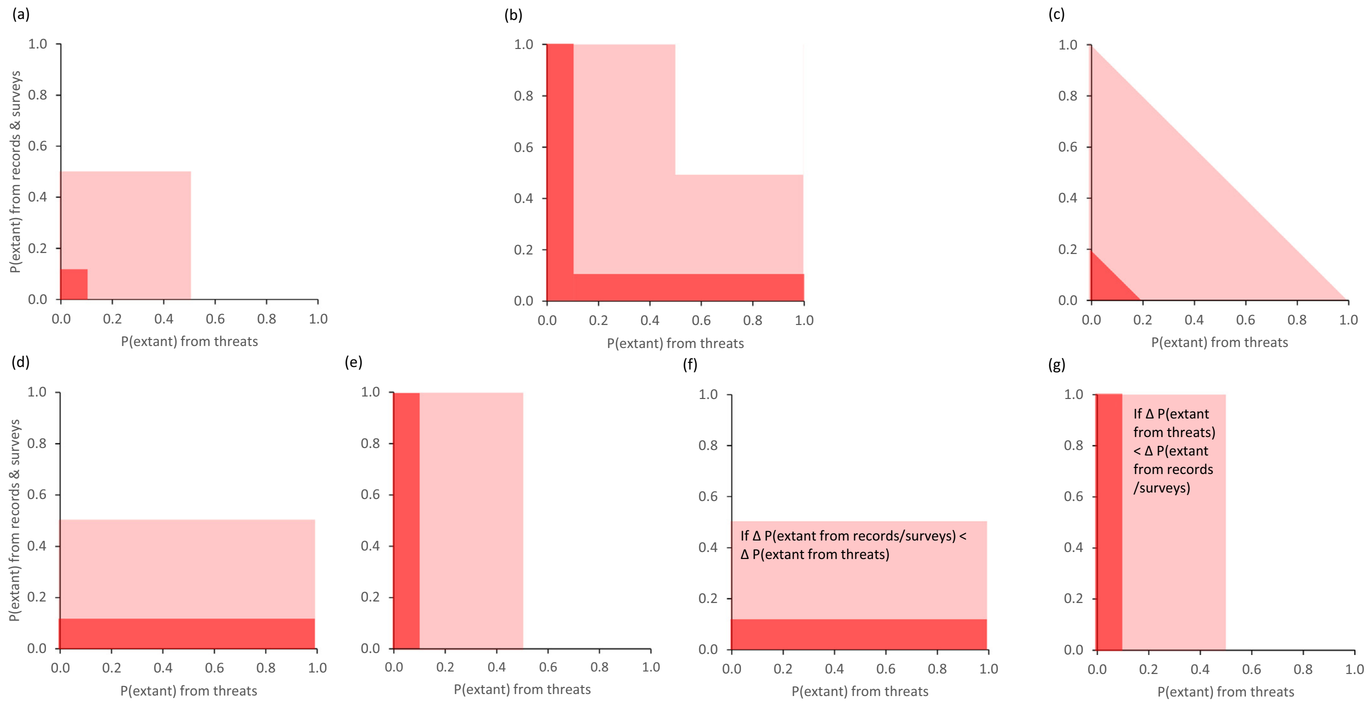


**Fig. 1.** The six approaches considered for determining which species should be listed as Critically Endangered (Possibly Extinct) and which as Extinct: (a) method 1: any species for which *both* P(extant based on records and surveys) *and* P(extant based on threats) were less than a threshold value; (b) method 2: any species for which *either* P(extant based on records and surveys) *or* P(extant based on threats) were less than a threshold value; (c) method 3: any species for which the *sum* of P (extant based on records and surveys) and P(extant based on threats) was less than a threshold value; (d) method 4: any species for which P(extant based on records and surveys) was less than a threshold value; (e) method 5: any species for which P(extant based on threats) was less than a threshold value; (f) and (g) method 6: any species for which the least uncertain of P(extant based on records and surveys) and P(extant based on threats) was less than a threshold value. For illustrative purposes, the thresholds are set as 0.5 for Possibly Extinct and 0.1 for Extinct for all methods except method 3, for which the thresholds are set as 1.0 for Possibly Extinct and 0.2 for Extinct. Coloured segments show the area of the graph in which species would qualify as Critically Endangered (Possibly Extinct) (pink) and Extinct (red) under each approach. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(updated from Szabo et al., 2012), and examined threats to species as coded by BirdLife International (2017) using the CMP/IUCN Threats classification scheme. Only threats coded as having medium or high impact were treated as potential drivers of extinctions, thus excluding threats with low, no/negligible and unknown impacts. As expected for known or suspected extinct species, most threats were coded as having a 'past impact', but in order to compare their importance (the magnitude of their impact) we scored them as 'current' using version 1.0 of the IUCN Threat Impact Scoring System (IUCN, 2012). We compared broad threat types at level 1 in the CMP/IUCN Threats classification scheme, but treated 'Natural System Modifications' and 'Biological Resource Use' at level 2, given they contain such diverse factors. This resulted in the identification of 324 separate threat-species combinations.

## 3. Results

For the 61 species considered, we compiled data on 819 records (range 1–67 per species, median 7) and 356 surveys (range 0–16 per species, median 6), estimating a total of 2070 probabilities associated with the threats to these species, the likely validity of records, the scope and adequacy of surveys, and passive surveillance levels (Appendix 1, see Table 1 for definitions of the parameters).

We then used these probabilities to calculate (using the methods from Keith et al., 2017 and Thompson et al., 2017, summarised in Appendix 2) the probability that a species remained extant. This ranged from 0.030 to 0.995 using data on threats, and from $6.238 \times 10^{-60}$ to 0.901 using data on records and surveys. The correlation between the two estimates for the same species was significantly positive ($R = 0.610$, $P < 0.001$), but with some notable outliers (Fig. 2).

Applying the estimated values to different methods and thresholds for determining which species should be listed as Critically Endangered (Possibly Extinct), we found that methods 1 and 3 produced the lowest rate of mismatches with current IUCN Red List Categories (14.8% at a threshold of 0.5 for both methods), while methods 2 and 4 produced a minimum rate of mismatches of 16.4% at thresholds of 0.2–0.3 and 0.4 respectively. Methods 5 and 6 had the highest rate of mismatches, with minima of 18.0% at thresholds of 0.3–0.4 and 0.4 respectively (Fig. 3). The ratio of different types of errors varied. Methods 1, 4 and 6 produced similar numbers of misclassified Critically Endangered species and Critically Endangered (Possibly Extinct) species, while most of the errors for methods 2 and 5 were Critically Endangered species misclassified as Possibly Extinct (8/10 and 8/11 respectively), with the converse being true for method 3 (2/9).

For defining Extinct species, most methods produced low rates of mismatches, with minima of 6.6% at values for P(extant) of 0.1 for method 1, 3.3% at 0.1–0.12 for method 3, 8.2% at 0.04–0.06 for method 4, and 6.6% at 0.06 for method 6. The highest rate of mismatches was produced by methods 2 and 5, with minima of 9.8% and 16.4% at values for P(extant) of 0.02–0.04 and 0.08–0.1 respectively. Although method 3 produced the lowest rate of mismatches, it is notable that no method misclassified any Extinct taxa at or above thresholds for P(extant) of 0.1, 0.04, 0.12, 0.08, 0.1 and 0.1 for methods 1–6 respectively. Mismatches above these thresholds related to currently Critically Endangered or Critically Endangered (Possibly Extinct) species being classified as Extinct by the methods.

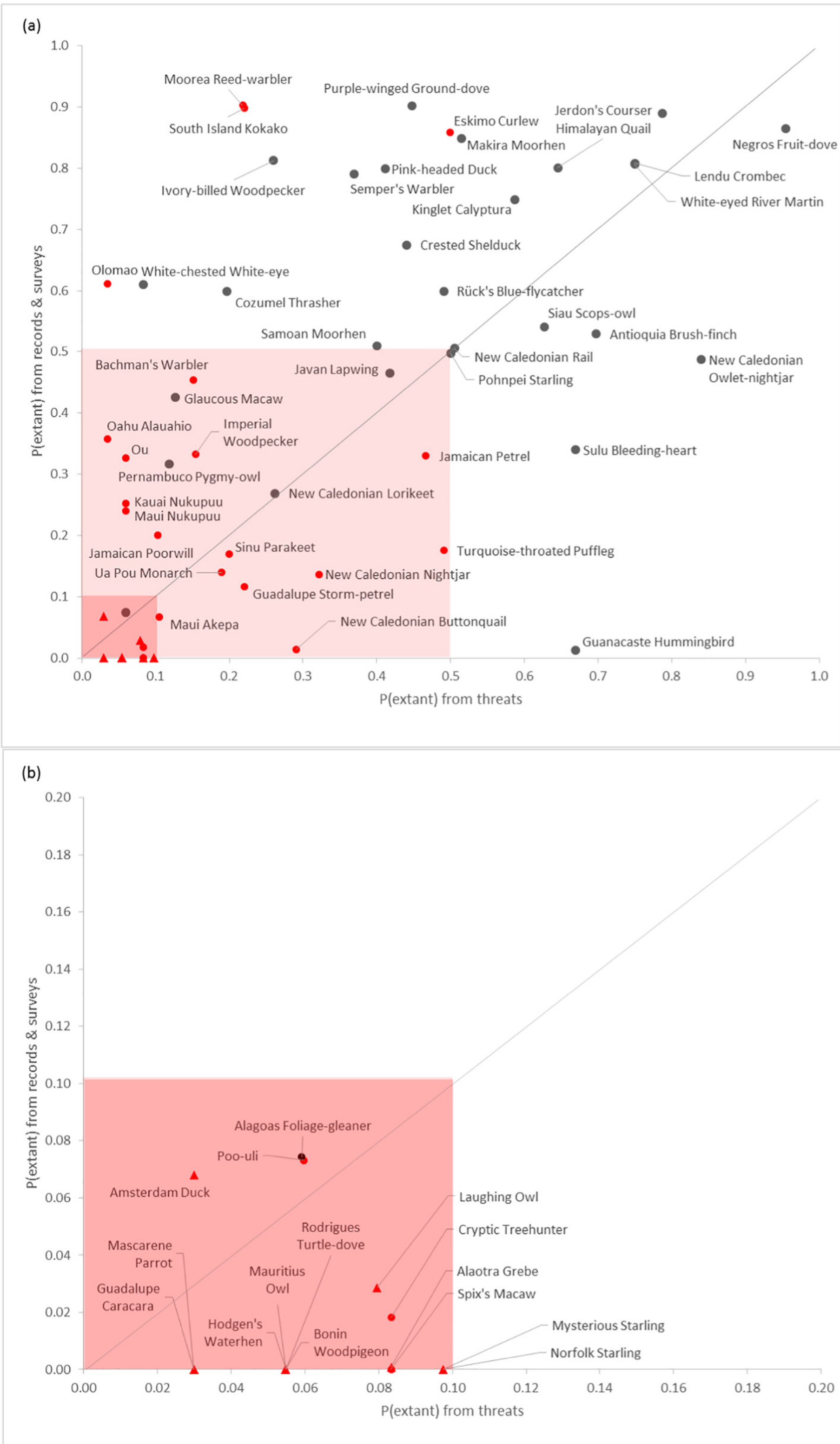


**Fig. 2.** Probability that bird species remain extant estimated from the timing and certainty of records and the timing and adequacy of surveys (y axis) and the severity, extent and timing of threats (x axis). Black dots represent species currently classified as Critically Endangered. Red dots represent species currently classified as Critically Endangered (Possibly Extinct) or Critically Endangered (Possibly Extinct in the Wild). Red triangles represent species currently classified as Extinct. The pink box shows the area of the plot falling below 0.5 on both axes (proposed boundaries for Possibly Extinct). The red box shows the area of the plot falling below 0.1 on both axes (proposed boundaries for Extinct). The solid line shows values where x = y. For clarity, species falling in the red box are not labelled in (a), but are shown in an expanded plot in (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## 4. Discussion

### *4.1. Assessing probability of extinction*

Compiling the data to apply the method for assessing P(extant based on surveys and records) took considerable effort, and estimating the relevant probabilities for records, surveys and threats inevitably involved a degree of subjectivity. In particular: some species are so poorly known that it is difficult to assess the importance of different threats and the susceptibility of species to them; some published records have so little detail and context that it is difficult to assess their validity; some surveys are described so briefly that it is difficult to determine their adequacy or the proportion of the species' potential distribution covered; and it is likely that some unsuccessful surveys were not

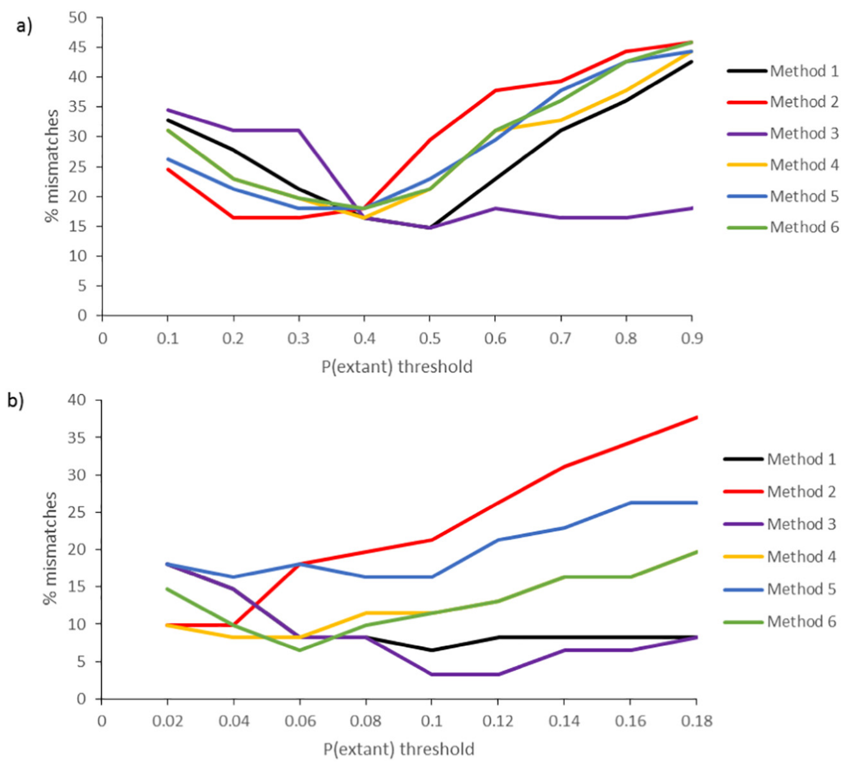


**Fig. 3.** Percentage of mismatches between predicted versus published IUCN Red List categories using different thresholds of P(extant) for classifying species as (a) Critically Endangered (Possibly Extinct), and (b) Extinct using method 1: (P(extant) based on both records/surveys and threats fall below the threshold), method 2: (P(extant) based on either records/surveys or threats falls below the threshold), method 3: (the sum of P(extant) based on records/surveys and threats falls below the threshold), method 4: P(extant) based on records/surveys falls below the threshold, method 5: P(extant) based on threats falls below the threshold, and method 6: the least uncertain of estimates of P(extant) based on records/surveys and P(extant) based on threats falls below the threshold. We tested thresholds for method 3 up to 1.5 for Critically Endangered (Possibly Extinct) species and up to 0.3 for Extinct species, but for clarity the X axis is truncated at 0.9 in (a) and 0.18 in (b).

included in the analysis because they are not documented in the literature. The time costs and challenge of maximising objectivity may discourage some potential users of the methods described by Keith et al. (2017) and Thompson et al. (2017). However, the principle benefits of these approaches are that they force assessors to be explicit and transparent about the significance given to different factors involved in deciding how to classify species, and that they promote greater consistency in these decisions. Given that all non-Data Deficient species are known from at least one specimen with information on its provenance, it should always be feasible to apply both approaches, with information on plausible threats inferred from related or ecologically similar species and/or from information on the spatial distribution of threats if no direct information is available on threats to the species (e.g. Joppa et al., 2016). If adopted more widely by assessors of species for the IUCN Red List, it will be important to test for and promote consistency in their application over time and between different species or taxonomic groups.

### 4.2. *Defining species as Critically Endangered (Possibly Extinct) or Extinct*

For heuristic purposes, we compared the current classifications of species as Critically Endangered, Critically Endangered (Possibly Extinct) and Extinct with those produced by applying six different methods to assign species to these three classes using different thresholds. All approaches correctly classified over 80% of species tested (Fig. 3), with methods 1 and 3 performing best for categorising species as Critically Endangered (Possibly Extinct), and method 3 followed by methods 1 and 6 performing best for categorising species as Extinct.

Regardless of the rate of mismatches, there are good reasons for not favouring methods 2, 5 and 6, which each use just one rather than both of the parameters P(extant based on records and surveys) and P(extant based on threats). This is because it is important to consider both sets of information in classifying species (Butchart et al., 2006). Furthermore, the risks and conservation costs of incorrectly listing an extant species as extinct are likely to outweigh those of making the opposite error (Akcakaya et al., 2017), so in cases where only one of the two P(extant) values falls below a threshold, it would be imprudent to base a classification on the lower P(extant) value alone. For example, Guanacaste hummingbird (*Amazilia alfaroana*) has a very low P(extant based on records and surveys) of 0.01 because there has been no record since the type specimen was collected in Costa Rica in 1895. However, this could simply be because nobody has searched for the species for many decades, partly because it has languished in taxonomic obscurity, having been elevated to species status only in 2016, with most resident and visiting birdwatchers and scientists in Costa Rica being unaware of its existence (Kirwan and Collar, 2016). Given that parts of the Volcán de Miravalles (from where the species was originally collected) appear to remain fairly well forested (Kirwan and Collar, 2016), it is unlikely that habitat loss could have driven the species extinct, hence it has a P (extant based on threats) of 0.67. With no other plausible threats, it seems premature to list the species as Possibly Extinct. Conversely, invasive alien species (particularly mongooses) and habitat loss could have plausibly driven Semper's warbler extinct on St Lucia, hence P (extant based on threats) = 0.37. However, recent searches have been far from sufficient, with P(extant based on records and surveys) estimated to be 0.79. Oppel (2016) estimated that their survey in 2016 (one of only five searches since 1931) spent less than one-tenth of the time needed to conduct a thorough search of the ten highest priority areas of potential habitat. Extremely high densities of venomous snakes in some areas and the presence of illegal marijuana cultivation were identified as impediments to more comprehensive surveys (Oppel, 2016). Hence it would be premature to list Semper's warbler as Possibly Extinct.

Although assessing both P(extant based on records and surveys) and P(extant based on threats) requires more data and effort, we do not think it should ever be impossible to apply both approaches, as information on both ought to be available for all non-Data Deficient taxa. Comparing the best performing approaches—methods 1 and 3—we note that the latter may be marginally less intuitive than method 1. We therefore recommend applying method 1 and a threshold of 0.5 for both P(extant based on threats) and P(extant based on records and surveys) to classify species as Critically Endangered (Possibly Extinct), and a threshold of 0.1 for both parameters for classifying species as Extinct.

Following this approach, it is instructive to examine the 12

**Table 2**
Species for which the predicted classification differed from their current listing. Recommended categories in bold indicate those cases in which no change is recommended.

| Species | P(extant) based on records & surveys | P(extant) based on threats | 2017 IUCN Red List category | Predicted category under method 1 with a threshold of 0.5 | Recommended category | Notes |
|---|---|---|---|---|---|---|
| Javan Lapwing *Vanellus macropterus* | 0.465 | 0.418 | CR | CR(PE) | CR(PE) | This species is known only from Java, Indonesia, where it inhabited marshes and river deltas. There are unsubstantiated claims that it occurred on Sumatra and Timor. It was described as local and uncommon, and has not been recorded since 1939. The fact that it was reputedly impossible to overlook suggests very strongly that it is no longer present at any site studied in recent decades by ornithologists. A series of surveys carried out since 1949 have failed to locate any individuals, but there are several unconfirmed reports from local people. High levels of human disturbance and conversion of its habitat to aquaculture and agricultural land, hunting and trapping were the main drivers of declines. |
| Eskimo Curlew *Numenius borealis* | 0.858 | 0.500 | CR(PE) | CR | **CR(PE)** | The last confirmed record was in 1963. While there have been many claims since, these all have a very low probability of being valid. |
| Pernambuco Pygmy-owl *Glaucidium mooreorum* | 0.317 | 0.118 | CR | CR(PE) | CR(PE) | Known only from Reserva Biológica de Saltinho, where two individuals were collected in 1980 and a recording was made in 1990, and a single record from Usina Trapiche in 2001, despite many extensive searches in forest fragments across Pernambuco and Alagoas. Extensive habitat loss and fragmentation, including loss of virtually all truly lowland forest, has occurred throughout the potential range. |
| Glaucous Macaw *Anodorhynchus glaucus* | 0.425 | 0.127 | CR | CR(PE) | CR(PE) | Formerly widespread but very local in north Argentina, south Paraguay, north-east Uruguay and Brazil from Paraná state southwards. It became rare before or early in the second half of the 19th century. There were a few local reports in the 20th century, with the last probable observations and local reports in Mbaracayu, Paraguay in the late 1990s and 2001. Loss of yatay palm habitat and capture for the cagebird trade are likely to have driven declines. |
| Spix's Macaw *Cyanopsitta spixii* | 0.00006 | 0.083 | CR(PEW) | EW | EW | Last known from near the rio São Francisco in north Bahia, Brazil, where only three birds remained in 1985–1986, and these were captured for trade in 1987 and 1988. However, a single male, paired with a female Blue-winged Macaw *Propyrrhura maracana*, was discovered at the site in July 1990, and survived until the end of 2000. There have no subsequent records of wild birds, despite searches and fieldworker presence in the area. An observation in 2016 in the Curaca area is believed to relate to a release from captivity. Loss of gallery woodland and trapping for the cagebird trade likely drove declines. |
| New Caledonian Lorikeet *Charmosyna diadema* | 0.269 | 0.262 | CR | CR(PE) | CR(PE) | Known from two specimens collected prior to 1860, reports published in 1913, and local reports in 1953/4, "1960s", and 1976, but no subsequent records despite searches and local interviews. Lowland habitat loss, introduced disease and/or invasive mammals (notably rats) are likely to have driven declines. |
| Cryptic Treehunter *Cichlocolaptes mazarbarnetti* | 0.018 | 0.083 | CR(PE) | EX | EX | Known only from Murici in Alagoas and Frei Caneca in Pernambuco, Brazil, from which it was last recorded in 2007 and 2005 respectively, despite subsequent intensive searches at both these localities. Severe habitat loss, fragmentation and disturbance has occurred throughout the likely historical range. |
| Alagoas Foliage-gleaner *Philydor novaesi* | 0.074 | 0.059 | CR | EX | EX | Only known from Murici, Alagoas and RPPN Frei Caneca, Pernambuco, Brazil, from which it was last recorded in 2007 and 2011 respectively, despite subsequent intensive searches at both these localities. Severe habitat loss, fragmentation and disturbance has occurred throughout the likely historical range. |
| South Island Kokako *Callaeas cinereus* | 0.898 | 0.220 | CR(PE) | CR | **CR(PE)** | Among numerous recent claims, records in 1967 and 2007 were accepted by the New Zealand Records Committee. The latter is controversial and arguably cannot be regarded as confirmed, given lack of multiple observers or any physical evidence. |

(*continued on next page*)

**Table 2** (*continued*)

| Species | P(extant) based on records & surveys | P(extant) based on threats | 2017 IUCN Red List category | Predicted category under method 1 with a threshold of 0.5 | Recommended category | Notes |
|---|---|---|---|---|---|---|
| Moorea Reed-warbler *Acrocephalus longirostris* | 0.894 | 0.218 | CR(PE) | CR | CR | The last record was in 1981, but there have been no searches since 1986–1987 apart from untargeted fieldwork in 2008, and there were unconfirmed records in the mid-1990s, 2003, 2008 and 2010. |
| Olomao *Myadestes lanaiensis* | 0.612 | 0.204 | CR(PE) | CR | **CR(PE)** | The last confirmed record was in 1980, but there were unconfirmed records in 1988, 1994 and 2005. The inaccessible Olokui Plateau (where the last records were) has not been surveyed since. However, it is so small (the entire Olokui natural area reserve is 6.6 $km^2$, but less than half is high elevation forest that would be suitable for Olomao) and it has been isolated for so long (several decades) that it is unlikely a population would have persisted. |
| Poo-uli *Melamprosops phaeosoma* | 0.073 | 0.060 | CR(PE) | EX | EX | Known only from Maui, Hawaiian Islands, where it was discovered in 1973, but declined rapidly during 1975–1985, with only 5–7 birds known in 1995, and only 3 by mid-1997, one of which was captured in September 2004 but died in November 2004; the other two have not been seen since 2003 and 2004. No other individuals have been located since 1998 despite intensive searches. Invasive mammals and diseases are likely to have driven declines. |

mismatches with current IUCN Red List categories (Table 2). Four species are currently classified as Critically Endangered, but based on our results we recommend that they should be reclassified as Critically Endangered (Possibly Extinct): Javan lapwing (*Vanellus macropterus*), glaucous macaw (*Anodorhynchus glaucus*), New Caledonian lorikeet (*Charmosyna diadema*), and Pernambuco pygmy-owl (*Glaucidium mooreorum*). Similarly, we recommend that three species are now listed as Extinct (cryptic treehunter (*Cichlocolaptes mazarbarnetti*), Alagoas foliage-gleaner (*Philydor novaesi*) and poo-uli (*Melamprosops phaeosomaii*)) and one as Extinct in the Wild (Spix's macaw (*Cyanopsitta spixii*); noting that birds survive in captivity, and there are long-term plans to reintroduce the species to the wild; BirdLife International, 2017). In most of these cases, their reclassification had already been considered by the authors as part of BirdLife International's ongoing updates of IUCN Red List assessments for all birds, but deferred pending the outcome of the current analysis.

In one case (Moorea reed-warbler (*Acrocephalus longirostris*)), the species is currently listed as Critically Endangered (Possibly Extinct), but we recommend reclassification as Critically Endangered: although the last confirmed record was in 1981, three unconfirmed reports since 2000 and the lack of any targeted searches since 1987 provide some hope that it may survive.

Three species currently classified as Critically Endangered (Possibly Extinct) would qualify for reclassification as Critically Endangered according to the analysis, but we do not recommend such changes: eskimo curlew (*Numenius borealis*), South Island kokako (*Callaeas cinereus*) and olomao (*Myadestes lanaiensis*); Table 2. For the first two of these, the modelled probability of species survival is higher than expected, and this is driven by numerous unconfirmed records since the last confirmed record. For example, there have been 23 unconfirmed records of eskimo curlew since the last widely accepted sighting in 1963. These were nearly all assigned probabilities of correct identification $p(ci)$ of 0.1–0.5. Even if these are reduced to 0.1–0.3, the probability of survival is only marginally reduced from 0.86 (0.81–0.91) to 0.85 (0.81–0.90). For such cases, the approach of Thompson et al. (2017) appears to generate implausibly high probabilities that taxa survive. This may be because the method treats all observations as independent, but it is likely that there are high levels of awareness of these high-profile species among a large pool of less-experienced birdwatchers and naturalists, who may be more likely to claim records of the species if they have heard of other such claims.

For olomao, habitat loss on the Hawaiian island of Molokai, and introduced pigs, deer and malaria are very likely to have driven the species extinct, hence P(extant based on threats) is very low (0.204, range: 0.1–0.307). P(extant based on records and surveys) is higher (0.61, 0.47–0.75). The last confirmed observations were of three individuals in 1980, when the population was estimated as 19 individuals (Scott et al., 1986). Three subsequent claims are considered unsubstantiated (Pyle and Pyle, 2009). The area of remaining habitat is tiny (the entire Olokui natural area reserve is 6.6 $km^2$, but less than half is high elevation forest that would be suitable for Olomao) and it has been isolated for so long (several decades) that it is unlikely that a population would have persisted (E. Vanderwerf *in litt*. 2017). Hence, although approaches tested here for estimating the probability that a species remains extant are valuable, there may be good grounds to override the outcomes in exceptional cases, particularly for high profile taxa with a suite of recent claims that are judged to be of low probability of being correct.

It is also worth noting that, during the preparation of this paper, two species that we had initially included in our analysis were rediscovered and confirmed as extant: Tachira antpitta (*Grallaria chthonia*) and Belem curassow (*Crax pinima*). Both had been correctly classified as Critically Endangered under the approach and thresholds proposed here: P(extant) based on threats and records/surveys = 0.575 and 0.729 respectively for Tachira antpitta, and 0.448 and 0.882 respectively for Belem Curassow.

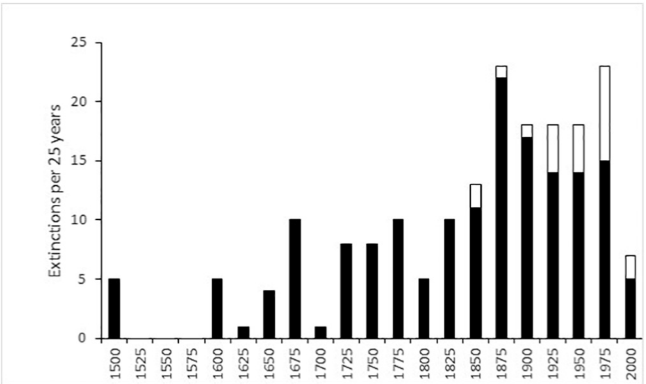


**Fig. 4.** Number of bird species that are confirmed (Extinct/Extinct in the Wild, solid bars) or suspected (Critically Endangered (Possibly Extinct), open bars) to have gone extinct per quarter-century. Values for the latest time period are for 2000–2017.

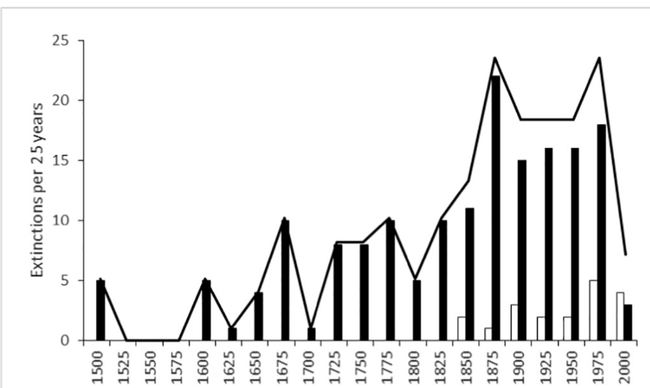


**Fig. 5.** Number of bird extinctions per quarter-century on continents (open bars), islands (solid bars) and in total (line).

Another advantage of the approach tested here is that it also allows quantification of the survey effort required in order to move species into Critically Endangered (Possibly Extinct) or into Extinct. For example, no surveys for olomao have been carried out on the Olokui Plateau since the last observations were made there in 1980 (Reynolds and Snetsinger, 2001; Pyle and Pyle, 2009). If surveys were carried out in 2018 covering the entire plateau (ε′ = 0.95–0.99) with a high probability of reliably identifying birds if they were detected (p(i) = 0.8–0.95, but recognising that the probability of recording this taxon is moderately low (p(r) = 0.3–0.7), this would reduce the calculated probability of survival to 0.36 (0.16–0.55), warranting reclassification of the species to Critically Endangered (Possibly Extinct). Equivalent surveys would need to be repeated each year up to 2021 in order to reduce the probability to 0.07 (0.06–0.08) qualifying the species for recategorisation as Extinct.

### 4.3. A revised analysis of extinction rates and drivers

Applying the recommended reclassifications of species listed in Table 2 allows an updated assessment of the rate of extinctions and their drivers (Butchart et al., 2006; Szabo et al., 2012). We estimate that 187 bird species are likely to have gone extinct since 1500, including 159 classified as Extinct, six as Extinct in the Wild and 22 as Critically Endangered (Possibly Extinct). This figure is marginally higher than the total estimated using the method described in Akcakaya et al. (2017), whereby 1-P(extant) is summed across all species assessed (with the mean for the sample of Extinct species applied to those Extinct species that were not assessed, and the same approach applied for Extinct in the Wild species). This yields a total of 185 extinctions using estimates of P(extant based on records and surveys) and 184 extinctions using estimates of P(extant based on threats). Fig. 4 illustrates the importance of including Extinct in the Wild and Critically Endangered (Possibly Extinct) species, particularly considering extinction rates over the last century or so. The estimate for the quarter-century starting in 2000 is an underestimate, given the date runs to 2017 only, and given time-lags in detecting extinctions.

Most bird extinctions (90%) have been of species restricted to islands, but the rate of continental extinctions is now increasing (Fig. 5). The main drivers, indicated as having had potentially a medium or high impact on these species, have been invasive species (implicated in 46% of extinctions), hunting and trapping (26%) and unsustainable agriculture (14%) (Fig. 6), matching the pattern described by Szabo et al. (2012).

## 5. Conclusions

We found the methods proposed by Keith et al. (2017) and

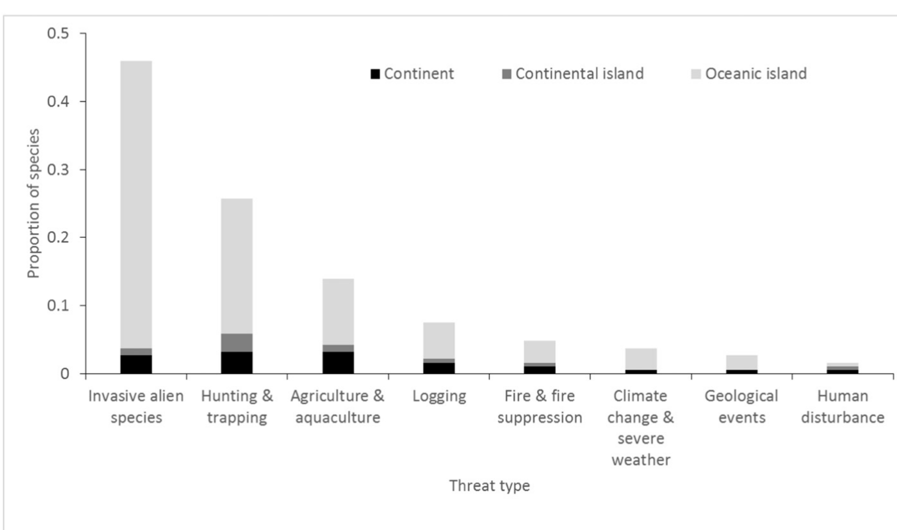


**Fig. 6.** Drivers of extinction for confirmed and suspected extinct bird species on continents (black bars), continental islands (dark grey bars) and oceanic islands (light grey bars). For clarity, drivers impacting two or fewer species are excluded.

Thompson et al. (2017) to be useful for increasing consistency in assessing the likelihood that species may have gone extinct, mainly through forcing assessors to consider all lines of evidence, and to be more explicit in the way that they weigh up different lines of evidence. By applying thresholds for the boundaries between Critically Endangered, Critically Endangered (Possibly Extinct) and Extinct, the approach also helps to increase consistency and transparency in assigning species these different statuses. However, the approach is best taken as a strong guide rather than an inflexible rule. For example, for mysterious starling (*Aplonis mavornata*) and Norfolk starling (*Aplonis fusca*), both P(local) and P(spatial) were scored as 0.9–1.0, yielding a best estimate of P(extant) of 0.098, marginally below the proposed threshold of 0.1 for Extinct. However, assigning them a value of 0.9–0.99 for each parameter would give a best estimate of P(extant) of 0.107, marginally above the proposed threshold of 0.1 for Extinct. Hence the final categorisation is sensitive to very small (arguably imperceptible) differences in the underlying parameter estimates. Furthermore, we find the algorithm of Thompson et al. (2017) gives undue weight to multiple recent records with low probability of being valid: we judge that both eskimo curlew and South Island kokako are far more likely to be extinct than estimated based on records and surveys, owing to numerous recent claims, none of which are judged very likely to be valid. The IUCN Red List Technical Working Group is now coordinating further testing of these methods for non-avian taxa by IUCN Species Specialist Groups, in order to explore the generality of our results, and appropriateness of our recommended approach for wider adoption by the IUCN Red List. Future work could also explore making greater use of the uncertainty of estimates of P(extant) in applying the approach recommended here.

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