Title: The impact of alternative metrics on estimates of Extent of Occurrence for extinction risk assessment

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Abstract

Extent of Occurrence (EOO) is a key metric in assessing extinction risk using the IUCN Red List categories and criteria. However, the way in which EOO is estimated from maps of species' distributions is inconsistent between assessments of different species, and between major taxonomic groups. It is often estimated from the area of mapped distribution, but these maps often exclude areas of unsuitable habitat in idiosyncratic ways and are not created at the same spatial resolutions. We assessed the impact on extinction risk categories of applying different methods for estimating EOO for 21,763 species of mammals, birds and amphibians. Overall, we found that the percentage of threatened species requiring downlisting to a lower category of threat, taking into account other Red List criteria under which they qualified, spanned 11-13% for all species combined (14-15% for mammals, 7-8% for birds and 12-15% for amphibians) depending on the method used. Extrapolating from birds for missing data for amphibians and mammals suggests that 14% of threatened and Near Threatened species potentially require downlisting using a Minimum Convex Polygon (MCP) approach, as now recommended by IUCN, with other metrics (such as alpha hull) having marginally smaller impacts. We conclude that uniformly applying the MCP approach will potentially lead to a one-time downlisting of hundreds of species, but ultimately ensure consistency across assessments and realign the calculation of EOO with the theoretical basis upon which the metric was founded.

Introduction

The International Union for Conservation of Nature's Red List of Threatened Species (hereafter IUCN Red List) serves as a global repository of knowledge on the extinction risk of species (Rodrigues *et al*. 2006, Vié *et al*. 2009). The Red List assessment process is based on an objective system allowing assignment of any species (except micro-organisms) to one of eight IUCN Red List Categories of extinction risk using criteria linked to population decline, size and geographic distribution (IUCN 2012ba, Mace *et al*. 2008, see Table 1 for a summary). The categories and criteria are designed to take account of the considerable uncertainty that often exists in the underlying data (Akçakaya *et al*. 2000). The process is managed to ensure authoritative review, and a petitions process is in place to handle disagreements or challenges to listings.

The IUCN Red List, compiled and produced by IUCN and its 10 Red List Partner institutions, is based on contributions from a network of thousands of scientific experts around the world, drawn from universities, museums, research institutes, NGOs and government institutions. The standards that are integral to the process are guarded by an independent authority, the Standards and Petitions Subcommittee (SPSC), and combine scientific rigor with the pragmatism needed to implement an assessment process at a global scale (Mace et al. 2008).

Each assessment is accompanied by extensive information covering taxonomy, geographic distribution, habitat requirements, biology, threats, population size, utilization, and conservation actions. Over the past 50 years the IUCN Red List has become instrumental in monitoring progress towards internationally agreed biodiversity conservation goals and commitments (Butchart *et al*. 2005, 2010, Tittensor *et al*. 2014).

An important recent advancement is the requirement (formerly not obligatory) to submit geo-referenced distribution maps for each species, preferably in electronic (GIS) format (IUCN 2012b). Such distribution maps now exist for ~50,000 species within the Red List. Geo-referenced distribution data are important for at least two reasons. First, these data are widely used in conservation planning (Hoffmann *et al*. 2008), and further they underpin a variety of analyses in the broader ecological literature. Much of what is understood about global patterns of biodiversity in relation to threat status stems from analyses of IUCN Red List distribution maps (e.g., Mace *et al*. 2005, Hoffmann *et al*. 2010, Collen et al. 2013, Jenkins *et al*. 2013, Pimm *et al*. 2014). Second, spatial distribution data are essential for supporting assessments made under Red List criteria B and D2, and specifically for informing whether or not species qualify under the area thresholds for Extent of Occurrence (EOO) and Area of Occupancy (AOO). However, there has been considerable inconsistency in the way in which these distribution data have been used to estimate EOO and AOO (e.g. Burgman & Fox 2003, Callmander et al. 2007, Uzunov et al. in: Rossi et al. 2008, Attore et al. 2011, Bachman et al. 2011, Rakotoarinivo et al. 2014). Here we strictly focus on the issues surrounding the calculation of EOO.

The central component of Criterion B1 is the extent to which risks from threatening factors are spread geographically across the native distribution of a species (Gaston 1991, 1994). This is encompassed by the concept of EOO, which is measured as "the area contained within the shortest continuous imaginary boundary which can be drawn to encompass all the known, inferred or projected sites of present occurrence of a taxon, excluding cases of vagrancy" (IUCN 2012a). Red List assessments have calculated EOO in a variety of ways, including alphahull and minimum convex polygon (MCP) algorithms, or by simply summing the area of the species' distribution map where it is extant (EDM). We detail these approaches below. The purpose of our analysis is to understand the potential impact on Red List assessments of using one of these methods (alphuall, MCP, EDM) versus another to calculate EOO. This was particularly motivated by the IUCN's Standards and Petitions Subcommittee's recent recommendation to strictly use an MCP to calculate EOO.

EOO is not intended to be an estimate of the amount of occupied or potential habitat nor a measure of the area over which a species is actually found to occur (although it may approach this for some species) (Gaston & Fuller 2009). EOO is largely scale independent, and is included in IUCN Red List criterion B as a metric of the degree of risk spread across populations; very simply, the larger the EOO, the less likely that all populations will undergo simultaneous extinction as a consequence of current or future threats (IUCN Standards and Petitions Subcommittee2014).

The theoretical basis for using EOO as a measure of risk spread is the observation that many environmental variables and processes are spatially correlated, meaning that locations situated more closely together experience more similar (more correlated) conditions over time than those far apart; and therefore populations close to each other often have correlated dynamics, which leads to higher overall extinction risk compared with populations spread over a larger area. Consistent application of EOO across taxonomic groups is essential for comparable accounting of extinction risk estimates.

The threshold for listing as Vulnerable under criterion B1 is an EOO estimated to be less than 20,000km^2 in conjunction with at least two of: (a) distribution severely fragmented or known to exist at no more than 10 locations (where location is defined by the threat); (b) continuing decline, observed, inferred or projected, in the extent of occurrence, area of occupancy, area, extent and/or quality of habitat, number of locations or subpopulations or number of mature individuals; or (c) extreme fluctuations in extent of occurrence, area of occupancy, number of locations or subpopulations or number of mature individuals.

As highlighted by Gaston & Fuller (2009), calculation of EOO has been characterised by considerable variation between assessments in the degree to which discontinuities or disjunctions within the overall distribution have been excluded, relating to both internal discontinuities ('holes' within the extent of distribution where the species is considered to be absent) and external discontinuities (areas of the distribution margin from which the species is considered to be absent, which can be highly complicated if mapped at a high resolution – see, for example, the coastal boundaries for *Mus musculus* (http://maps.iucnredlist.org/map.html?id=13972)). The *IUCN Red List Categories and Criteria* (IUCN 2012a) note that EOO 'can often be measured by a Minimum Convex Polygon (MCP; the smallest polygon in which no internal angle exceeds 180 degrees and which contains all the sites of occurrence)'. MCPs do not exclude discontinuities (i.e. have no 'holes' within them), and many assessments have used this metric (e.g. Callmander et al. 2007, Bachman et al. 2011, Rakotoarinivo et al. 2014); others have used alpha-hull algorithms (which provide an objective method of excluding discontinuities in the species range) (Burgman & Fox 2003, Uzunov et al. in: Rossi et al. 2008, Attore et al. 2011). However, many assessments (e.g. all 10,039 bird species and most of the >5,000 mammal species on the Red List) have calculated EOO by summing the area of all polygons in the species extant distribution map, with these polygons excluding areas of unsuitable habitat occurring within the geographic distribution of a species. Such exclusion has been undertaken using a variety of different approaches. At one extreme, measures of EOO can approach the AOO (defined by IUCN 2012a, following Gaston (1991, 1994) as the area that is occupied by a taxon), for which different thresholds are specified within the Red List.

This inconsistency in the extent to which EOO estimates include discontinuities has partly been precipitated by a difference between the official *IUCN Red List Categories and Criteria* (version 3.1; IUCN 2012a), which were formally adopted in 2001 and have remained unchanged since, and the more regularly updated *Guidelines for Using the IUCN Red List Categories and Criteria* (maintained by IUCN's independent Standards and Petitions Subcommittee). While the former notes that EOO '… may exclude discontinuities or disjunctions within the overall distributions of taxa (e.g. large areas of obviously unsuitable habitat)', it does not specify the conditions under which this may be done. Meanwhile the guidelines have, at least since 2006, discouraged such exclusions for estimating EOO (but not for determining change in EOO over time; see below). Version 5.0, for example (IUCN Standards and Petitions Working Group 2006), notes "exclusion of areas forming discontinuities or disjunctions from estimates of EOO is discouraged except in extreme circumstances". The most recent version of the guidelines (version 11; SPSC 2014), while acknowledging the IUCN Red List Categories and Criteria, contain the most emphatic wording yet to discourage such exclusions ("…for assessments of criterion B, exclusion of areas forming discontinuities or disjunctions from estimates of EOO is strongly discouraged").

The guidelines make a distinction between calculating EOO for inferring reduction or decline (e.g. for criteria A2(c) or B2b(i)), and for comparing against the thresholds in criterion B1. For inferring reduction or decline, the guidelines recommend excluding discontinuities by calculating alphahulls, so that trend estimates are less affected by fluctuating occurrences in the margins of a species' distribution. However, for calculating EOO for criterion B1, the guidelines strongly discourage this because disjunctions and outlying occurrences accurately reflect the extent to which a larger area of geographic distribution reduces the likelihood that the entire population of the taxon will be affected by a single threatening process.

Given the availability of various tools for easily and rapidly computing MCP from distribution data (Bachman *et al*. 2011), the simplest way to address this inconsistency between assessments would be to require strict application of MCPs (following Gaston's 1991, 1994 and Gaston & Fuller's 2009 recommendations) to calculate EOO for criterion B1. However, given that, as is the case for all bird species and most mammal species on the Red List, many assessments include EOO estimates based on the summed area of EDMs, a concern is that this could lead to destabilization of the Red List, with potentially large numbers of species requiring reclassification. In particular, for species listed under criterion B based on an EOO estimate derived from a distribution map that excludes unsuitable habitat, strict use of MCP to re-calculate EOO could increase the estimate of EOO sufficiently that the species would need to be 'downlisted' to a lower category of threat because it no longer meets the threshold for the category in which it is currently listed. Although there are clear benefits from improving the consistency and accuracy of extinction risk assessments, wholesale downlisting of large suites of species at one time could be perceived negatively by some users of the Red List who may have to make substantial readjustments to conservation priorities as a consequence of the revised estimates of extinction risk.

The analysis presented here should be placed within the context of evolving *Guidelines for Using the IUCN Red List Categories and Criteria* and the availability of tools to aid this process. As noted above, historically a range of approaches for calculation of EOO have been used, and many assessments have taken the area of the EDM as an estimate of EOO. Given this context we investigate the potential impact of the IUCN Standards and Petitions Subcommittee's current guidelines to use a strict MCP for calculating EOO. We do so by quantifying the impact of applying different methods for estimating EOO from distribution maps (including different approaches to dealing with internal and external discontinuities) thus representing a range of approaches used in past assessments. Specifically, we compare EOO estimates using several different methods for each species (alphahulls, MCP and EDM), and finally show how these different estimates would affect the resulting Red List categories for species in these three groups.

Methods

Data

Spatial data for 5,412 mammals and 6,312 amphibians on the IUCN Red List were obtained from IUCN (2014), and those for 10,039 birds were obtained from BirdLife International and NatureServe (2012) for a total of 21,763 species. Of those, a total of 4,455 species (amphibians: 1,952, mammals: 1,194, birds: 1,309) were threatened. A further 1,583 species were listed as Near Threatened (NT), but of those we only had criterion information for the 867 NT bird species. Approximately 69% of threatened amphibians, 44% of threatened mammals, and 33% of threatened birds are listed, potentially among other criteria, under B1.

Calculating EOO

Following IUCN (2012a) and IUCN Standards and Petitions Subcommittee (2014), to calculate EOO from each species' original distribution map (here termed ODM) we considered only those polygons where Origin is coded as 'Native' (= 1) or 'Reintroduced' (= 2) and Presence is coded as 'Extant' (=1) (we also included the legacy coding of 2 for Presence [formerly 'Probably Extant], although this has now been dropped from the IUCN polygon attributes for newer assessments). We also excluded those for which seasonal occurrence was set as 'unknown', and for migratory species we took the smaller of the sum of the area of resident+breeding distribution or resident+non-breeding distribution (IUCN 2012b). All analyses were performed using the language R (R Core Team 2014). We refer to the resulting distribution maps as the Extant Distribution Map of each species.

For all species listed as Critically Endangered, Endangered, Vulnerable (collectively, "threatened")) or Near Threatened, we then used the EDM to calculate potential estimates of EOO as follows (computational details are provided in the SI):

i) Area of (dissolved) polygons within the EDM.

ii) Area of MCP around EDM.

iii) Area of alphahull (alpha parameter = 3), by sampling 1,000 points from inside the EDM.

Figure 1 provides examples of the spatial outcomes of these calculations for the Great Indian Bustard *(Ardeotis nigriceps*).

Assessing potential impacts of different EOO estimates on extinction risk assessments

We applied these different EOO estimates to the IUCN Red List Category thresholds to assess the degree to which species would potentially require downlisting according to the different estimates. The three tests are:

1) Considering only criterion B1 regardless of any other criteria that the species qualified under. Hence, a species was treated as potentially requiring downlisting if the EOO estimate using a particular metric no longer fell below the relevant category threshold, even if the species was also listed at that category under another criterion. For example, if a species was listed as Endangered under criteria B1 and A2, and our revised estimate of EOO using a particular metric was above the threshold for Endangered (5,000 km^2), we treated it as no longer qualifying for

Endangered.

2) Considering criterion B1 and also taking into account any other criteria that the species qualified under. Hence, a species would not be regarded as potentially requiring downlisting if the EOO using a particular metric no longer fell below the relevant category threshold and if the species was also listed under another criterion. For example, if a species was listed as Endangered under criteria B1 and A2, and our estimate of EOO using a particular metric was above the threshold for Endangered (5,000 km^2), we treated it as remaining Endangered, but under A2 only (and not under B1 owing to the revised EOO estimate).

3) Considering all criteria the species was listed under at the category level at which it qualified, but also taking into account any other criteria they may have been listed under at *lower category levels*. This assessment was applied to birds only, because this is the only taxonomic group with comprehensive information available on the criteria under which they qualify at category levels below those at which they are listed. For example, if a species was listed as Critically Endangered under B1 and Endangered under A2, and our estimate of EOO using a particular method was above the threshold for Endangered, we treated it as requiring downlisting to Endangered, rather than Vulnerable or lower.

We examined the number of species requiring downlisting to lower categories of threat, but not the number that might require uplisting to higher categories of threat, because for a species to qualify at a particular category under criterion B1 requires not only for the EOO to fall below the relevant threshold, but also for the species to qualify under two of three subcriteria (see Introduction; IUCN 2012b, Table 1). Data on these parameters relevant to the subcriteria were not available for most taxa. If we had ignored them and assigned Red List categories using EOO alone, we would have greatly inflated estimates of extinction risk, as many species have sufficiently small EOOs, but occur at too many locations or have insufficiently fragmented subpopulations to qualify for the requisite subcriteria.

The Red List Categories and Criteria do not specify a threshold value of EOO that may qualify a species as Near Threatened when it “approaches the thresholds” for Vulnerable under criterion B1. However, following the examples given in IUCN Standards and Petitions Subcommittee (2014), we treated EOO estimates larger than or equal to 30,000 km^2 as qualifying the species as Least Concern, and 20,000-29,999 km^2 as qualifying the species for Near Threatened, notwithstanding the caveats above.

From these analyses, we assessed the potential impact on IUCN Red List categorisations of different approaches to calculating EOO.

RESULTS

Potential impact of revised EOO estimates on Red List categories

The percentage of species with EDM equating to the MCP was just 0.8% for birds, 4.3% for mammals and 21.7% for amphibians, while the mean proportion of MCP that EDM comprised was 53% across all three groups. Given the IUCN Standards and Petitions Subcommittee’s current guidelines to use a strict MCP for calculating EOO, this suggests that it is inappropriate for the vast majority of assessments to simply use the range extent (EDM) as an estimate of EOO and to apply this to Criterion B1.

Under Test 1 (considering only categorizations under criterion B1, and ignoring other criteria under which species may qualify), the percentage of threatened bird, mammal and amphibian species combined requiring downlisting by at least one category was 18% using MCP and 16% using alphahull (Table 2; further details in SI Tables 3a,b). Overall, the percentages requiring downlisting were similar between taxa (e.g. using MCP they ranged from 17.6% for birds to 18.6% for mammals), but averaged highest for mammals. Perhaps the most significant practical implications from such downlistings occur when a species moves from a threatened category to a non-threatened category (Near Threatened or Least Concern). The percentage of threatened bird, mammal and amphibian species combined requiring downlisting to a non-threatened category was 10% using MCP and 8% using alphahull (These and remaining results are found in Table 2 with further details in SI Table 3a). Numbers of species used to calculate percentages are available in SI Table 3b.

Test 2, taking into account the other criteria under which species are listed (especially criteria A, C and D, relating to rate of decline and population size), reduced the proportion of all species potentially requiring downlisting by at least one category by just more than one-quarter, with a similar reduction for the proportion of threatened species potentially requiring downlisting to a non-threatened category. The percentage of threatened bird, mammal and amphibians species requiring downlisting by at least one category was 13% using MCP and 11% using alphahull. The equivalent numbers for threatened bird, mammal and amphibian species requiring downlisting to a non-threatened category were 7% and 5%.

Test 3, where we also took into account the criteria coded for categories lower than that at which the species is actually listed (focusing on birds as this is the only group with such data available), resulted in both fewer species being downlisted by one or more categories and fewer threatened species being downlisted to non-threatened status compared with Test 1 and Test 2. For example, using MCP, 8.3% of bird species qualified for downlisting by one or more categories (compared with 17.6% in Test 1 and 8.4% in Test 2), and 3.6% of threatened species qualified for downlisting to non-threatened categories (compared with 11.9% in Test 1 and 5.1% in Test 2).

Depending on the test employed, the additional information on Near Threatened species available for birds changed the percent of bird species downlisted very little, with the largest effects (a reduction of 1.9%) seen in Test 1 using MCP.

Impact of calculating EOO with MCP on Red List statistics

Certain categories will bear the largest burden of downlistings (SI Table 3b). For example, under Test 1 the number of Endangered birds, mammals, and amphibians combined that would be downlisted by at least one category is 355 (reduced to 285 under Test 2), while only 124 Critically Endangered species would be downlisted. While we do not have access to the data for Near Threatened amphibian and mammal species, our Test 2 and 3 results for birds suggest that Near Threatened taxa in these groups will also require a large number of downlistings (SI Table 3b). For example, there are 867 Near Threatened bird species, of which 127 (15%) are listed under B1 only. Under Tests 2 and 3, 65 (51%) bird species qualified for downlisting to Least Concern.

If we assumed that these same Test 3 ratios hold for amphibians and mammals, then of the 397 Near Threatened amphibians and 319 Near Threatened mammals we can expect 60 and 48, respectively, to be listed under B1 only, and 31 and 25 of them to be downlisted to Least Concern. Overall, we estimate that of the 4,455 bird, amphibian, and mammal species in categories CR, EN, VU, and NT, 637 (14%) will be downlisted by one or more categories, and 3% of the 21,673 mammals, birds and amphibians currently assessed on the Red List are likely to be downlisted at least one category.

The percentage of species in these three taxonomic groups that will move from threatened to non-threatened categories is low. Extrapolating from the test 3 result (3.6% of bird species moving from threatened to non-threatened) to all birds, mammals, and amphibians would result in an additional 161 species considered as non-threatened. This would have a negligible effect on the overall percentage of species considered threatened (CR, EN, or VU) across all three groups, reducing from 20.6% to 19.8%.

Discussion

The IUCN's Standards and Petitions Subcommittee's recommendation to use an MCP to calculate EOO, without excluding internal discontinuities, is based on the fact that an MCP is 1) closest to the original concept of EOO (according to which, the thresholds were originally set), 2) the most straightforward to compute, 3) relatively robust to variation in the resolution of spatial data available to assessment groups (as we show in SI Figure 2, map resolution can vary widely between species and taxonomic groups), and 4) has no arbitrary settings to implement.

The use of different standardized methods to calculate EOO had a marked influence on the number of species listed under Criterion B1 that qualified for downlisting to lower categories of threat. Using alphahulls (including different values for alpha; see Supplementary Information) slightly reduced the proportion of species potentially requiring downlisting compared with using MCP. Yet the use of alphahulls introduces its own computational uncertainties, including unconstrained and ecologically arbitrary options on parameter values and the number of sampling points to include (here we used a fixed number for each species). Nor is it clear how alphahulls relate to the original theory underlying the concept of EOO as a measure of the spread of extinction risk.

Maps as supporting documentation

The IUCN Standard and Petition Subcommittee's strong guidance for the use of an MCP, and our results on the impact of those recommendations, clarify the role of distribution maps in the assessment process. As justified in IUCN (2012b), the two primary roles are: 1) to give an indication of the geographic distribution or range of the species and to support conservation through, for example, systematic conservation planning, research or as a communication tool for the general public, or decision makers and donors; and 2) to inform and support assessments of species under criteria B and D2 and specifically calculation of EOO and AOO. Problems emerged in the past when assessors started using the outputs of this first purpose to inform the second (especially calculation of EOO) by simply treating the area of distribution based on distribution maps (here termed EDM) as synonymous with EOO, a conceptual issue complicated further in the literature by calls for more refined mapping of distributions to inform EOO estimation (Harris & Pimm 2008; Simaika & Samways 2010; Pena et al. 2014).

This is problematic because mapped distribution in effect often becomes conceptually closer to AOO as one maps with greater accuracy. New mapping technology, the availability of detailed forest cover maps (Hansen *et al*. 2013), other base layer boundaries, and geospatial modeling techniques have improved our ability to map species distributions at ever increasing accuracy. Consequently more species qualify as threatened under the B1 criterion (as originally pointed out by Gaston & Fuller 2009). For broader conservation planning, research and communication purposes, the objective of creating distribution maps should always be to produce the most accurate depiction of a taxon's distribution according to available knowledge and data, in the format that is considered most appropriate for that taxon, ensuring that the basis of the map is adequately documented.

For Red List assessments under criteria B and D2 and the calculation of EOO the objective should always be the consistent application of the IUCN Red List categories and criteria. Detailed distribution maps may be used to inform calculation of EOO, but only by using it as the input parameters for deriving an MCP and not for direct derivation of area thresholds (Gaston & Fuller 2009).

We consider three possible circumstances in which there are known potential limitations to the strict application of MCP to calculate EOO (Standards and Petitions Subcommittee 2014): (1) curvilinear distributions (e.g., species distributed in a river or mountain chain (such as the Eastern Arc mountains of Tanzania), or in a narrow band along coastlines (such as mangroves and many shorefishes); (2) doughnut distributions, with large areas of unoccupied range in the centre of the distribution (e.g., species restricted to shallow waters on the periphery of a lake, or to low-elevations on a mountain, such as Grand Comoro Scops-owl *Otus pauliani*, or with coastal distributions around a land-mass, such as Island Cisticola *Cisticola haesitatus* or Cocos Stargazer *Gillellus chathamensis*); and (3) highly disjunct populations (e.g., where the majority of the population occurs on a large land-mass with an additional population on one or more small distant islands, such as Cuckoo Roller *Leptosomus discolor*). In the case of arc-shaped distribution, the 'curve' in the linear distribution substantially increases the EOO estimate. However, this is appropriate as it reflects the fact that extinction risk is spread in two dimensions. For linear distributions, MCP may lead to an overestimate of extinction risk (IUCN Standards and Petitions Subcommittee 2014), but this is also true for other metrics. For doughnut distributions, the consequence of the configuration of their distribution should be to reduce, not increase, extinction risk for threats that are also restricted to similar distributions. Finally, for species with small and highly disjunct subpopulations, there is no obvious theoretical basis upon which to exclude the unsuitable habitat (Gaston 1994). The highly disjunct nature of the distribution accurately reflects the spread of risk to the species, which would substantially increase if either part of the distribution were to be lost. Furthermore, it would be difficult to establish a consistent rule as to what qualifies as highly disjunct. Consequently, in all three situations outlined above, we suggest that it is most appropriate not to permit any exceptions to application of MCP to estimate EOO. Also, in these cases EOO is not the only measure of geographic distribution available for use as part of a species' assessment. For instance, species that have a discontinuous distribution (a main criticism of the use of MCP to calculate EOO) can still be assessed under criterion B2 using measures of their AOO, and indeed may qualify at higher categories of extinction risk under this criterion.

Our results show that strict adherence to the guidance provided in IUCN Standards and Petitions Subcommittee (2014) in not excluding unsuitable habitat could result in hundreds of species listed under Criterion B1 being downlisted to lower categories of threat. However, these species make up less than ~3% of all birds, mammals, and amphibians currently assessed on the Red List. Furthermore, our analysis shows that a comparable degree of downlisting would result even with objective measures of excluding discontinuities (such as alphahull). With the majority of species yet to be assessed (Stuart *et al*. 2010), the risk of further inconsistency within and across taxa can be avoided by wholesale adoption of the MCP approach from now on, while the potential impact is still low.

We conclude that a single, relatively resolution-independent measure to calculate EOO (MCP) – as recommended by current IUCN Red List guidelines – will allow for assessments across species and taxonomic groups to be comparable over space and time and will ensure far greater consistency across the Red List. Finally, we note that there is a need for empirical testing of the assumptions underlying the interpretation of EOO. Better information on the spread or contagion of different types of threat would allow scientists to validate these assumptions, and allow work to begin on refining metrics and guidelines for measuring the effect of spatial structure on the likelihood that all populations of a species will undergo simultaneous extinction as a consequence of current or future threats.

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Figure 1

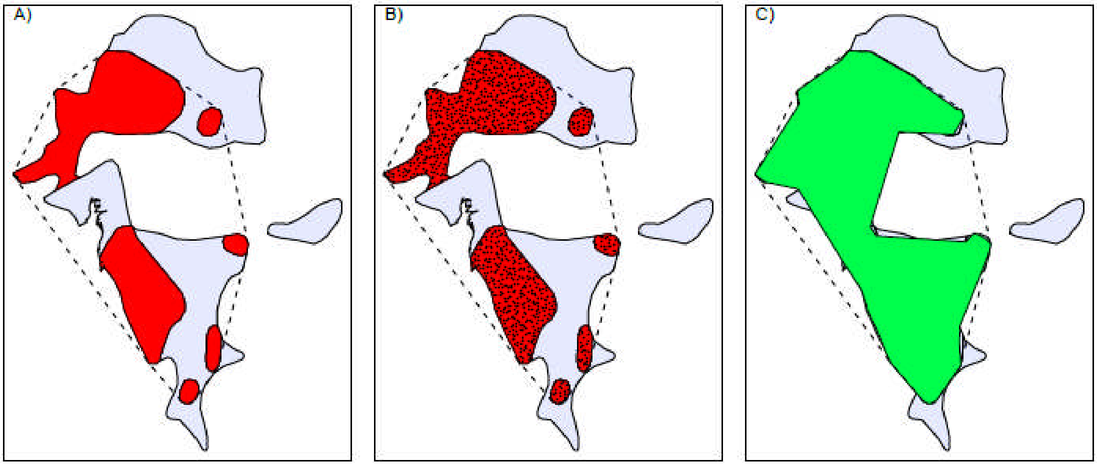

Figure 1: Example, using the Great Indian Bustard *Ardeotis nigriceps*, of the spatial subsetting and EOO metric calculations (Minimum Convex Polygon – MCP, and Alphahull –parameter 3). **A**: The distribution map for *Ardeotis nigriceps*. Red indicates where the species is coded as Native and Extant. Grey indicates where the species is coded as Native but Extirpated. Total area of the species distribution (grey+red) is 1,115,668km^2, while the area of the Extant Distribution Map (EDM, red) is 464,213km^2.. **B**: Black dots show the 1,000 sampled points used to initialize the alphahull algorithm. **C**: Spatial outcomes of alphahull algorithm (967,122km^2). In all figures the dashed line shows the MCP around the EDM (1,355,706km^2)

Table 1

Criterion	Critically Endangered	Endangered	Vulnerable	qualifiers and notes
A1: reduction in population size	≥90%	≥70%	≥50%	over 10 years/3 generations in the past, where causes are reversible, understood and have ceased
A2–4: reduction in population size	≥80%	≥50%	≥30%	over 10 years/3 generations in past, future or combination
B1: small range (extent of occurrence)	<100 km^2	<5000 km^2	<20 000 km^2	plus two of (a) severe fragmentation/few localities (1, %5, %10), (b) continuing decline, (c) extreme fluctuation
B2: small range (area of occupancy)	<10 km^2	<500 km^2	<2000 km^2	plus two of (a) severe fragmentation/few localities (1, %5, %10), (b) continuing decline, (c) extreme fluctuation
C: small and declining population	<250	<2500	<10 000 mature individuals.	Continuing decline either (1) over specified rates and time periods or (2) with (a) specified population structure or (b) extreme fluctuation
D1: very small population	<50	<250	<1000	mature individuals
D2: very small range	N/A	N/A	<20 km^2 or ≤5 locations	capable of becoming critically endangered or extinct within a very short time
E: quantitative analysis	≥50% in 10years/3 generations	≥20% in 20 years/5 generations	≥10% in 100 years	estimated extinction-risk using quantitative models, e.g. population viability analyses

Table 1: Simplified summary of the Red List categories and criteria. Reproduced from Butchart *et al* 2005.

Table 2

Analysis	Result	Taxa (N)	MCP (%)	AlphaHull (%)
Test 1. Considering only B1 and ignoring other criteria	% threatened species requiring downlisting at least 1 category	All	18.22	15.65
		Amphibians	18.43	15.52
		Mammals	18.61	16.62
		Birds	17.57	14.94
	% threatened species requiring downlisting to non-threatened category	All	10.09	7.73
		Amphibians	9.70	7.26
		Mammals	8.72	6.63
		Birds	11.92	9.43
	% threatened and NT species requiring downlisting at least 1 category	Birds	15.68	13.45
Test 2. Taking into account other criteria at the same category level	% threatened species requiring downlisting at least 1 category	All	13.05	11.14
		Amphibians	14.77	12.14
		Mammals	15.33	13.59
		Birds	8.40	7.42
	% threatened species requiring downlisting to non-threatened category	All	7.14	5.41
		Amphibians	8.36	6.25
		Mammals	7.37	5.62
		Birds	5.12	3.98
	% threatened and NT species requiring downlisting at least 1 category	Birds	8.04	7.36
Test 3. Taking into account other criteria at all category levels	% threatened species requiring downlisting at least 1 category	Birds	8.33	7.42
	% threatened species requiring downlisting to non-threatened category	Birds	3.59	3.14
	% threatened and NT species requiring downlisting at least 1 category	Birds	8.00	7.36

Table 2. Percentage and number of species requiring downlisting for each approach to estimating EOO and under different conditions. Metrics are: Minimum Convex Polygon (MCP); Alphahull, Parameter = 3, without internal discontinuities.

SI Table 1: Percentage and number of species requiring downlisting for each approach to estimating EOO and under different conditions. Metrics are: Metric 1a (RadarScan 1^{o}); Metric 1b (RadarScan 10^{o}); Metric 2a (alphahull, Parameter = 3, without internal discontinuities), Metric 2b (alphahull, Parameter = 3, with internal discontinuities), Metric 3a (alphahull, Parameter = 2, without internal discontinuities), Metric 3b (alphahull, Parameter = 2, with internal discontinuities), Metric 4 (Minimum Convex Polygon).

SI Table 2: Spearman rank correlation between each EOO metrics for each species. The number of pairwise comparisons made for each calculation is also indicated.

SI Table 3a: Percentage of species in each Red List category qualifying for downlisting using estimates for EOO derived from each metric. *N*: the number of species considered for each calculation. *CR-EN*: Critically Endangered to Endangered, *CR-VU:* Critically Endangered to Vulnerable, *CR-LC:* Critically Endangered to Least Concern, *EN-VU:* Endangered to Vulnerable, *EN-LC:* Endangered to Least Concern, and *VU-LC:* Vulnerable to Least Concern).

SI Table 3b: Same as SI Table 2a, but reporting the total number of species in each category.

SI Table 4: EOO estimates (total area in km2) for each metric for each species, plus the number of polygons, polygon vertices, internal discontinuities, and internal discontinuity vertices in the distribution map.

SI Tables 'Test 1', 'Test 2', 'Test 3': The original and projected Red List category for each species using EOO estimates derived from each metric for each of the three tests (e.g. Test 1 corresponds to SI_Table_Test_1). Column descriptions are provided as embedded comments in SI_Table_Test_3.

SI Figure 1: Example, using the Great Indian Bustard *Ardeotis nigriceps*, of the spatial subsetting and EOO metric calculations. **A**: The distribution map for *Ardeotis nigriceps*. Red indicates where the species is coded as Native and Extant. Grey indicates where the species is coded as Native but Extirpated. Total area of the species distribution (grey+red) is 1,115,668km^2, while the area of the Extant Distribution Map (EDM, red) is 464,213km^2. The dashed line shows the MCP around the EDM (Metric 4 -1,355,706km^2). **B**: Black dots show the 1,000 sampled points used to initialize the alphahull algorithm (Metrics 2a,b, 3a,b). **C**: Spatial outcomes of Metric 3a (alpha parameter set to 3.0 - 967,122km^2). **D:**Spatial outcomes of Metric 2a (alpha parameter set to 2.0 - 708,766km^2).No internal discontinuities resulted from these calculations and thus Metrics 2a and 2b are equivalent, as are Metrics 3a and 3b. **E:** Example of how the RadarScan algorithm was calculated (Metrics 1a and 1b). *Black polygons*: EDM as in Figure 1 red subset. Green rectangle: shows the bounding box of the ENR, with the red dot showing the centroid of this. The blue circle has a radius equal to the length of the hypotenuse of the right triangle drawn from the bounding box, and the purple lines are drawn from the centroid to the blue circle, starting at 0 degrees and moving counterclockwise in 1 degree intervals, intersecting the ENR boundary. Black dots show the furthest intersection between every purple line and the ENR boundary. For clarity, only the first 33% of degree intervals (purple lines) are shown. **F**: Spatial outcomes of Metric 1a (768,695km^2).Polygons are created by connecting the sets of furthest intersecting points for each purple line. The MCP around the EDM (as in panel A) is shown by dashed line.**G & H**: Same as E & F, but for Metric 1b (H: 601,874km^2).

SI Figure 2: Illustration of calculations performed using a simplified schematic based on the Impala *Aepyceros melampus* where area in red represents its extant range. Summary statistics were calculated for: (i) the total number of polygons representing extant range (labelled A-B); (ii) the total area of polygons (area in red); (iii) the total number of internal discontinuities (labelled C); (iv) the total area of those discontinuities (total area of C) (v) the total number of polygon vertices (indicated by circles and triangles); (vi) and total number of vertices making up the internal discontinuities across the entire range map vertices (indicated by triangles).

SI Figure 3: Proportion of amphibian, bird and mammal species with different numbers of A) polygons, B) internal discontinuities, C) polygon vertices and D) internal discontinuity vertices in their complete mapped distributions. Figures are plotting the results of a histogram calculation where the x axis spans the minimum and maximum values, broken into increments by 0.05.

SI Figure 4: Proportion of species with different values for the ratio between EDM and MCP (a value of 1 indicates that the ENR equals the MCP). Figures are plotting the results of a histogram calculation where the x axis spans the minimum and maximum values, broken into increments by 0.05. Data points are greater than the x axis value to their left, and less than or equal to the x axis values to their right.