

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

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36

37 **Abstract**

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

59 **Introduction**

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

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

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

85 An important recent advancement is the requirement (formerly not obligatory)  
86 to submit geo-referenced distribution maps for each species, preferably in  
87 electronic (GIS) format (IUCN 2012b). Such distribution maps now exist for  
88 ~50,000 species within the Red List. Geo-referenced distribution data are  
89 important for at least two reasons. First, these data are widely used in

90 conservation planning (Hoffmann *et al.* 2008), and further they underpin a  
91 variety of analyses in the broader ecological literature. Much of what is  
92 understood about global patterns of biodiversity in relation to threat status  
93 stems from analyses of IUCN Red List distribution maps (e.g., Mace *et al.* 2005,  
94 Hoffmann *et al.* 2010, Collen *et al.* 2013, Jenkins *et al.* 2013, Pimm *et al.* 2014).  
95 Second, spatial distribution data are essential for supporting assessments made  
96 under Red List criteria B and D2, and specifically for informing whether or not  
97 species qualify under the area thresholds for Extent of Occurrence (EOO) and  
98 Area of Occupancy (AOO). However, there has been considerable inconsistency  
99 in the way in which these distribution data have been used to estimate EOO and  
100 AOO (e.g. Burgman & Fox 2003, Callmander *et al.* 2007, Uzunov *et al.* in: Rossi *et al.*  
101 *et al.* 2008, Attore *et al.* 2011, Bachman *et al.* 2011, Rakotoarinivo *et al.* 2014). Here  
102 we strictly focus on the issues surrounding the calculation of EOO.

103 The central component of Criterion B1 is the extent to which risks from  
104 threatening factors are spread geographically across the native distribution of a  
105 species (Gaston 1991, 1994). This is encompassed by the concept of EOO, which  
106 is measured as “the area contained within the shortest continuous imaginary  
107 boundary which can be drawn to encompass all the known, inferred or projected  
108 sites of present occurrence of a taxon, excluding cases of vagrancy” (IUCN  
109 2012a). Red List assessments have calculated EOO in a variety of ways, including  
110 alphahull and minimum convex polygon (MCP) algorithms, or by simply  
111 summing the area of the species’ distribution map where it is extant (EDM). We  
112 detail these approaches below. The purpose of our analysis is to understand the  
113 potential impact on Red List assessments of using one of these methods  
114 (alphahull, MCP, EDM) versus another to calculate EOO. This was particularly  
115 motivated by the IUCN’s Standards and Petitions Subcommittee’s recent  
116 recommendation to strictly use an MCP to calculate EOO.

117 EOO is not intended to be an estimate of the amount of occupied or potential  
118 habitat nor a measure of the area over which a species is actually found to occur  
119 (although it may approach this for some species) (Gaston & Fuller 2009). EOO is  
120 largely scale independent, and is included in IUCN Red List criterion B as a  
121 metric of the degree of risk spread across populations; very simply, the larger

122 the EOO, the less likely that all populations will undergo simultaneous extinction  
123 as a consequence of current or future threats (IUCN Standards and Petitions  
124 Subcommittee2014).

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

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

142 As highlighted by Gaston & Fuller (2009), calculation of EOO has been  
143 characterised by considerable variation between assessments in the degree to  
144 which discontinuities or disjunctions within the overall distribution have been  
145 excluded, relating to both internal discontinuities ('holes' within the extent of  
146 distribution where the species is considered to be absent) and external  
147 discontinuities (areas of the distribution margin from which the species is  
148 considered to be absent, which can be highly complicated if mapped at a high  
149 resolution – see, for example, the coastal boundaries for *Mus musculus*  
150 (<http://maps.iucnredlist.org/map.html?id=13972>)). The *IUCN Red List*  
151 *Categories and Criteria* (IUCN 2012a) note that EOO 'can often be measured by a  
152 Minimum Convex Polygon (MCP; the smallest polygon in which no internal angle

153 exceeds 180 degrees and which contains all the sites of occurrence)'. MCPs do  
154 not exclude discontinuities (i.e. have no 'holes' within them), and many  
155 assessments have used this metric (e.g. Callmander et al. 2007, Bachman et al.  
156 2011, Rakotoarinivo et al. 2014); others have used alpha-hull algorithms (which  
157 provide an objective method of excluding discontinuities in the species range)  
158 (Burgman & Fox 2003, Uzunov et al. in: Rossi et al. 2008, Attore et al. 2011).  
159 However, many assessments (e.g. all 10,039 bird species and most of the >5,000  
160 mammal species on the Red List) have calculated EOO by summing the area of all  
161 polygons in the species extant distribution map, with these polygons excluding  
162 areas of unsuitable habitat occurring within the geographic distribution of a  
163 species. Such exclusion has been undertaken using a variety of different  
164 approaches. At one extreme, measures of EOO can approach the AOO (defined by  
165 IUCN 2012a, following Gaston (1991, 1994) as the area that is occupied by a  
166 taxon), for which different thresholds are specified within the Red List.

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

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

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

214 The analysis presented here should be placed within the context of evolving  
215 *Guidelines for Using the IUCN Red List Categories and Criteria* and the availability  
216 of tools to aid this process. As noted above, historically a range of approaches for

217 calculation of EOO have been used, and many assessments have taken the area of  
218 the EDM as an estimate of EOO. Given this context we investigate the potential  
219 impact of the IUCN Standards and Petitions Subcommittee's current guidelines to  
220 use a strict MCP for calculating EOO. We do so by quantifying the impact of  
221 applying different methods for estimating EOO from distribution maps  
222 (including different approaches to dealing with internal and external  
223 discontinuities) thus representing a range of approaches used in past  
224 assessments. Specifically, we compare EOO estimates using several different  
225 methods for each species (alphahulls, MCP and EDM), and finally show how  
226 these different estimates would affect the resulting Red List categories for  
227 species in these three groups.

## 228 **Methods**

### 229 *Data*

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

### 239 *Calculating EOO*

240 Following IUCN (2012a) and IUCN Standards and Petitions Subcommittee (2014),  
241 to calculate EOO from each species' original distribution map (here termed ODM)  
242 we considered only those polygons where Origin is coded as 'Native' (= 1) or  
243 'Reintroduced' (= 2) and Presence is coded as 'Extant' (=1) (we also included the  
244 legacy coding of 2 for Presence [formerly 'Probably Extant'], although this has  
245 now been dropped from the IUCN polygon attributes for newer assessments).  
246 We also excluded those for which seasonal occurrence was set as 'unknown', and



247 for migratory species we took the smaller of the sum of the area of  
248 resident+breeding distribution or resident+non-breeding distribution (IUCN  
249 2012b). All analyses were performed using the language R (R Core Team 2014).  
250 We refer to the resulting distribution maps as the Extant Distribution Map of  
251 each species.

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

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

257 ii) Area of MCP around EDM.

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

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

## 262 *Assessing potential impacts of different EOO estimates on extinction risk* 263 *assessments*

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

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

275           Endangered.

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

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

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

305           The Red List Categories and Criteria do not specify a threshold value of EOO that

306 may qualify a species as Near Threatened when it “approaches the thresholds”  
307 for Vulnerable under criterion B1. However, following the examples given in  
308 IUCN Standards and Petitions Subcommittee (2014), we treated EOO estimates  
309 larger than or equal to 30,000 km<sup>2</sup> as qualifying the species as Least Concern,  
310 and 20,000-29,999 km<sup>2</sup> as qualifying the species for Near Threatened,  
311 notwithstanding the caveats above.

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

## 314 **RESULTS**

### 315 *Potential impact of revised EOO estimates on Red List categories*

316 The percentage of species with EDM equating to the MCP was just 0.8% for birds,  
317 4.3% for mammals and 21.7% for amphibians, while the mean proportion of  
318 MCP that EDM comprised was 53% across all three groups. Given the IUCN  
319 Standards and Petitions Subcommittee’s current guidelines to use a strict MCP  
320 for calculating EOO, this suggests that it is inappropriate for the vast majority of  
321 assessments to simply use the range extent (EDM) as an estimate of EOO and to  
322 apply this to Criterion B1.

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

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

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

356

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

360

### 361 *Impact of calculating EOO with MCP on Red List statistics*

362 Certain categories will bear the largest burden of downlistings (SI Table 3b). For  
363 example, under Test 1 the number of Endangered birds, mammals, and  
364 amphibians combined that would be downlisted by at least one category is 355  
365 (reduced to 285 under Test 2), while only 124 Critically Endangered species  
366 would be downlisted. While we do not have access to the data for Near  
367 Threatened amphibian and mammal species, our Test 2 and 3 results for birds  
368 suggest that Near Threatened taxa in these groups will also require a large

369 number of downlistings (SI Table 3b). For example, there are 867 Near  
370 Threatened bird species, of which 127 (15%) are listed under B1 only. Under  
371 Tests 2 and 3, 65 (51%) bird species qualified for downlisting to Least Concern.

372 If we assumed that these same Test 3 ratios hold for amphibians and mammals,  
373 then of the 397 Near Threatened amphibians and 319 Near Threatened  
374 mammals we can expect 60 and 48, respectively, to be listed under B1 only, and  
375 31 and 25 of them to be downlisted to Least Concern. Overall, we estimate that of  
376 the 4,455 bird, amphibian, and mammal species in categories CR, EN, VU, and NT,  
377 637 (14%) will be downlisted by one or more categories, and 3% of the 21,673  
378 mammals, birds and amphibians currently assessed on the Red List are likely to  
379 be downlisted at least one category.

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

### 387 **Discussion**

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

396 The use of different standardized methods to calculate EOO had a marked  
397 influence on the number of species listed under Criterion B1 that qualified for  
398 downlisting to lower categories of threat. Using alphahulls (including different  
399 values for alpha; see Supplementary Information) slightly reduced the

400 proportion of species potentially requiring downlisting compared with using  
401 MCP. Yet the use of alphahulls introduces its own computational uncertainties,  
402 including unconstrained and ecologically arbitrary options on parameter values  
403 and the number of sampling points to include (here we used a fixed number for  
404 each species). Nor is it clear how alphahulls relate to the original theory  
405 underlying the concept of EOO as a measure of the spread of extinction risk.

#### 406 *Maps as supporting documentation*

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

421 This is problematic because mapped distribution in effect often becomes  
422 conceptually closer to AOO as one maps with greater accuracy. New mapping  
423 technology, the availability of detailed forest cover maps (Hansen *et al.* 2013),  
424 other base layer boundaries, and geospatial modeling techniques have improved  
425 our ability to map species distributions at ever increasing accuracy.

426 Consequently more species qualify as threatened under the B1 criterion (as  
427 originally pointed out by Gaston & Fuller 2009). For broader conservation  
428 planning, research and communication purposes, the objective of creating  
429 distribution maps should always be to produce the most accurate depiction of a  
430 taxon's distribution according to available knowledge and data, in the format

431 that is considered most appropriate for that taxon, ensuring that the basis of the  
432 map is adequately documented.

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

438 We consider three possible circumstances in which there are known potential  
439 limitations to the strict application of MCP to calculate EOO (Standards and  
440 Petitions Subcommittee 2014): (1) curvilinear distributions (e.g., species  
441 distributed in a river or mountain chain (such as the Eastern Arc mountains of  
442 Tanzania), or in a narrow band along coastlines (such as mangroves and many  
443 shorefishes); (2) doughnut distributions, with large areas of unoccupied range in  
444 the centre of the distribution (e.g., species restricted to shallow waters on the  
445 periphery of a lake, or to low-elevations on a mountain, such as Grand Comoro  
446 Scops-owl *Otus pauliani*, or with coastal distributions around a land-mass, such  
447 as Island Cisticola *Cisticola haesitatus* or Cocos Stargazer *Gillellus chathamensis*);  
448 and (3) highly disjunct populations (e.g., where the majority of the population  
449 occurs on a large land-mass with an additional population on one or more small  
450 distant islands, such as Cuckoo Roller *Leptosomus discolor*). In the case of arc-  
451 shaped distribution, the 'curve' in the linear distribution substantially increases  
452 the EOO estimate. However, this is appropriate as it reflects the fact that  
453 extinction risk is spread in two dimensions. For linear distributions, MCP may  
454 lead to an overestimate of extinction risk (IUCN Standards and Petitions  
455 Subcommittee 2014), but this is also true for other metrics. For doughnut  
456 distributions, the consequence of the configuration of their distribution should  
457 be to reduce, not increase, extinction risk for threats that are also restricted to  
458 similar distributions. Finally, for species with small and highly disjunct  
459 subpopulations, there is no obvious theoretical basis upon which to exclude the  
460 unsuitable habitat (Gaston 1994). The highly disjunct nature of the distribution  
461 accurately reflects the spread of risk to the species, which would substantially  
462 increase if either part of the distribution were to be lost. Furthermore, it would

463 be difficult to establish a consistent rule as to what qualifies as highly disjunct.  
464 Consequently, in all three situations outlined above, we suggest that it is most  
465 appropriate not to permit any exceptions to application of MCP to estimate EOO.  
466 Also, in these cases EOO is not the only measure of geographic distribution  
467 available for use as part of a species' assessment. For instance, species that have  
468 a discontinuous distribution (a main criticism of the use of MCP to calculate  
469 EOO) can still be assessed under criterion B2 using measures of their AOO, and  
470 indeed may qualify at higher categories of extinction risk under this criterion.

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

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

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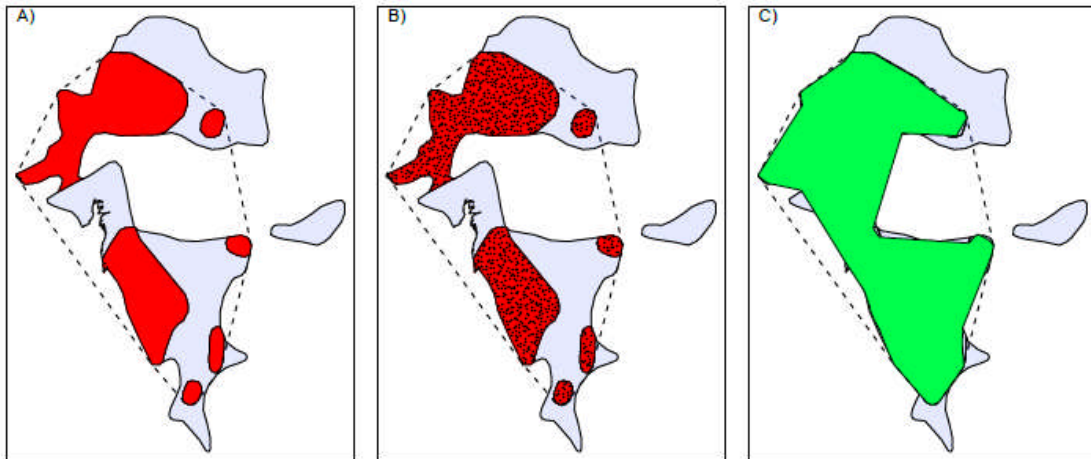
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631 **Figure 1**



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633 **Figure 1:** Example, using the Great Indian Bustard *Ardeotis nigriceps*, of the spatial  
634 subsetting and EOO metric calculations (Minimum Convex Polygon – MCP, and  
635 Alphahull –parameter 3). **A:** The distribution map for *Ardeotis nigriceps*. Red indicates  
636 where the species is coded as Native and Extant. Grey indicates where the species is  
637 coded as Native but Extirpated. Total area of the species distribution (grey+red) is  
638 1,115,668km<sup>2</sup>, while the area of the Extant Distribution Map (EDM, red) is 464,213km<sup>2</sup>.  
639 **B:** Black dots show the 1,000 sampled points used to initialize the alphahull algorithm.  
640 **C:** Spatial outcomes of alphahull algorithm (967,122km<sup>2</sup>). In all figures the dashed line  
641 shows the MCP around the EDM (1,355,706km<sup>2</sup>)

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**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 <sup>2</sup>	<5000 km <sup>2</sup>	<20 000 km <sup>2</sup>	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 <sup>2</sup>	<500 km <sup>2</sup>	<2000 km <sup>2</sup>	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 <sup>2</sup> 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

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

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673 **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°); Metric 1b (RadarScan 10°); 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 km<sup>2</sup>) 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<sup>2</sup>, while the area of the Extant Distribution Map (EDM, red) is 464,213km<sup>2</sup>. The dashed line shows the MCP around the EDM (Metric 4 -1,355,706km<sup>2</sup>). **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<sup>2</sup>). **D:** Spatial outcomes of Metric 2a (alpha parameter set to 2.0 - 708,766km<sup>2</sup>). 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<sup>2</sup>). 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<sup>2</sup>).

**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.