

Article

The Sweet Spot: A Holistic Method of Taxonomically Adjusted Range Delineation for Global Unification

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Simple Summary

Accurately mapping species distributions is essential for effective wildlife conservation, yet the methods used to delineate species ranges vary considerably, limiting consistency and comparability across regions and taxonomic groups. This study evaluates three commonly used approaches to range mapping: political boundaries, manually drawn boundaries, and model-based boundaries. We propose a standardized method based on taxon-specific minimum segment lengths (straight lines between vertices used to draw ranges) to improve the sensitivity and consistency of species range maps while limiting unnecessary polygon complexity. We recommend segment lengths ranging from 1.13 to 3.40 km, with most taxonomic groups falling between 2 and 3 km. Using two species as examples, we demonstrate the advantages of this approach over existing methods. We recommend combining species distribution models with expert knowledge and verified occurrence records to produce reliable range maps. Continued data collection and targeted field surveys are also essential to refine species distributions. Our approach provides a practical and globally applicable framework to improve species range delineation, facilitate comparisons across taxa, and support evidence-based conservation planning.

Abstract

Wildlife conservation is an increasing necessity as well as a challenge, partially due to the absence of a consistent framework among countries. One of the basic needs for conservation planning is species range delineation, where a variety of methods are used for mapping species distributions, reflecting the variety in parties providing data as well as the tools and methods used to determine boundaries. So far, a unified method that can be adopted for all types of data and taxonomic units is absent. Here, we compare the advantages and drawbacks of the three main types of range delineation methods found in the literature: political, hand-drawn, and modelling boundaries. Further, we present a pragmatic and holistic method to determine a taxonomically adjusted minimum segment length, defined as the distance connecting any two vertices and which end-to-end alignment can be used for drawing ranges for all animal taxa, derived from the median of all species' range area within a taxonomic unit. Our recommended minimum segment lengths vary from 1.13 km to 3.40 km (at the equator), with the value for most taxonomic groups being between two and three kilometers. Using two example species, we demonstrate the efficacy of our



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method in comparison to other methods in terms of sensitivity and unnecessary polygon complexity, and advocate for the combination of model outputs and expert knowledge using our recommended segment lengths. We encourage range maps to be drawn in consideration of known occurrence records and highlight the value of the continual collection of range data both from citizen science and targeted surveys. Overall, our recommendation guides conservation planners towards a unified method to delineate ranges that can be globally adopted.

Keywords: boundaries; distribution; species range; conservation planning

1. Introduction

Conservation awareness is steadily increasing worldwide. However, the process remains slow and is hindered by various synergetic factors [1,2]. The current rate of species loss, primarily resulting from anthropogenic activities, is developing into a sixth mass extinction [3], and the rate of extinction is escalating despite a general understanding of the main drivers of the biodiversity crisis [4,5]. Among the factors resulting in unsatisfactory conservation outcomes is the absence of global standards [6,7], with one of these inconsistent facets being the description of species ranges.

Knowing where a species occurs is a key first step for conservation actions [8]. The presence of a species is generally determined through a combination of direct and indirect methods, such as field surveys, satellite tracking, environmental DNA, literature review, and citizen science data collection [9]. These data are then combined to create range maps, also called distribution maps. However, distribution maps are highly variable in their making and presentation, even within the frame of leading organizations such as the Red List of Threatened Species from the International Union for Conservation of Nature [10]. The variation in methods for creating range maps is generally linked to the varied forms and amounts of species presence data, which vary widely between taxa [11,12]. In addition, the variety of methods for drawing boundaries greatly complicates comparisons between species or between taxa, and a harmonized approach is lacking.

As the distribution of species shifts, locally because of habitat loss, diseases, invasive species, and other anthropogenic disturbances [13], and globally due to climate change [14,15], it is important to generalize the baseline used to facilitate range descriptions and updates. In general, there are three main types of delineation methods, with ranges typically defined by political boundaries, expert hand-drawn boundaries, or model outputs. Here, we examine advantages and drawbacks for each type of range boundary and suggest a holistic and biologically informed method to standardize the description of species' range worldwide.

1.1. Political Boundaries

Some range delineations are based purely on political boundaries. A typical example is that of species ranging in the United States of America whose boundaries are sometimes drawn from the binary encoding of the presence of a species for each county (e.g., [16]; Figure 1A). The advantage of this type of map is that its boundaries are familiar and can easily inform conservation decision makers as to what species fall within their respective jurisdictions. However, these range boundaries are highly artificial, as species rarely follow political borders. For example, numerous species documented in southern China or in southeast Asia have boundaries following political borders instead of geographic features [17]. Exceptions exist though when political boundaries follow landscape patterns, such as coastal lines for terrestrial species or mountain ridges for lowland specialists.

In addition, political boundaries can occasionally reflect different policies, such as how differences in carrion management have divided the distribution of scavenging birds neatly along the border between Spain and Portugal [18]. However, these exceptions are not the norm and boundaries derived from political borders generally have a high degree of artificiality and inaccuracy, though they are easily understandable.

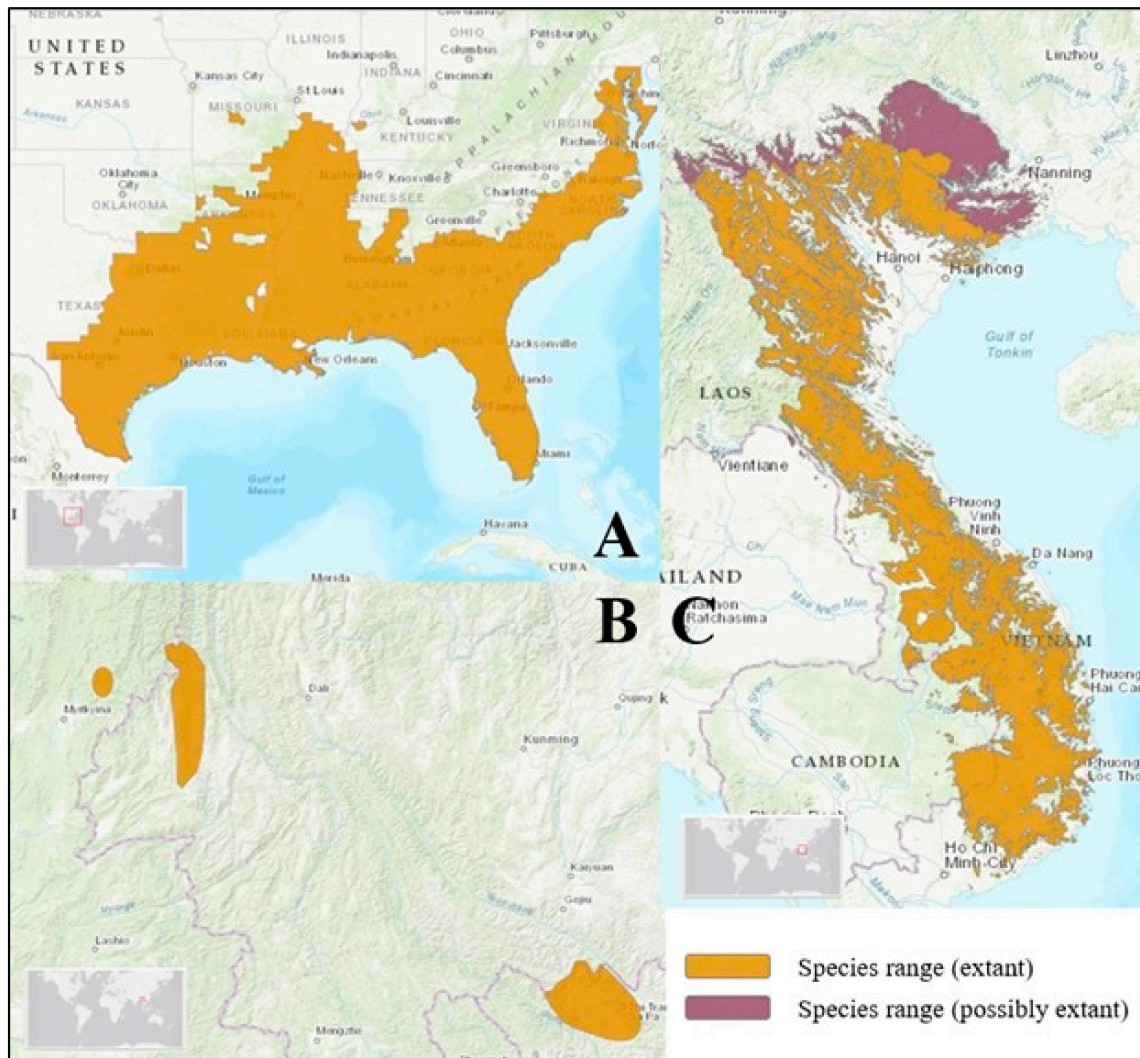


Figure 1. Examples of range map types. Types of range maps include those based on political divisions for counties and landscape barriers for coastal areas: (A) *Dryophytes cinereus* [16]; hand-drawn maps, which often vary across country borders; (B) *Bufo pageoti* [19]; and (C) binary outputs from ecological niche models (*Ingerophrynus galeatus*; [20]).

1.2. Hand-Drawn Boundaries

Hand-drawn boundaries are another type of range delineation, typically created by experts based on known occurrences of the species (e.g., [19,21]; Figure 1B). Such maps are relatively easy to produce and tend to be more biologically informed than maps drawn according to political boundaries as they are generally outlined with consideration of habitat types and biogeographic barriers. However, the level of detail and accuracy vary widely and are dependent on the knowledge of the expert drawing the map [22]. This can present challenges for species that occur in multiple countries with varying amounts of available biodiversity data. For instance, a skink species (*Scincella huanrenensis*) was assessed as occurring only at its type locality for an IUCN Red List assessment despite the literature showing the species to also be present in a different country a few hundred kilometers

away [23]. Hand-drawn maps, particularly non-digital ones, also can be low resolution and include relatively more unsuitable habitat than the model-based alternative described below [24]. Overall, while expert hand-drawn maps are more biologically relevant than political maps, their accuracy and usefulness are highly dependent on the expertise and effort of those drawing the map.

1.3. Modelling Boundaries

The third type of range delineation is based on ecological niche model (sometimes referred to as species distribution model or habitat suitability model) outputs (Figure 1C) generated by software tools such as Maxent or Wallace. The ecological models can be used to determine the range of species, either through ecological correlations based on a range of biotic and abiotic variables relating to the occurrence of the species, or through mechanistic models including ecological and physiological aspects [25,26]. The software-generated models are also useful as these can predict the presence of species in areas lacking records, often leading to the discovery of unknown populations [27]. Model outputs can be very precise when high-resolution data is available, such as the 30 s bioclimatic variables, though this can result in range boundaries that are oddly shaped and precise to an unrealistic degree (Figure 1C). Another difficulty is that while typical range maps are binary, indicating areas of presence, ecological niche models are inherently probabilistic. This means that converting a habitat suitability model into a binary range map loses the underlying nuance of the model, and high-resolution input data results in highly jagged boundaries (Figure 1C). Furthermore, resulting range maps will vary depending on the threshold used to convert a habitat suitability model into a binary range map [28,29]. The accuracy of models is also dependent on model inputs [30,31], and researchers ought to follow guidelines for quality and reproducibility [32,33]. Another important consideration is that theoretical landscape suitability does not equate to presence, as the species may simply not be there (e.g., IUCN SSC ASG [20,23]), therefore making ground truthing an important but infrequently done component of determining species' range. Yet, in general, ecological niche models are excellent for improving the understanding of a species' distribution, even if they are not perfect for mapping.

1.4. A Novel, Harmonized Approach

We propose that species range maps should be created with a taxonomically adjusted minimum segment length, defined as the distance connecting any two vertices with variable angles and which end-to-end alignment can be used to match the distribution of species, providing an appropriate level of precision and providing a way to harmonize expert maps and ecological niche models. Hand-drawn maps are often too imprecise, and maps from models tend to be precise to an unrealistic degree. Our novel approach reconciles both of these major disadvantages, creating range maps that are more realistic, biologically informed, and comparable.

2. Materials and Methods

2.1. Walk Through to a Unified Range Delineation Method

Ideally range maps would be drawn with an appropriate level of precision. Not all species have the same size of ranges, and it is reasonable to use a longer segment size for those that tend to have larger ranges. To determine an appropriate segment size, we first calculated the median range size of various taxonomic groups. The range shapefiles for a total of 64,787 species were downloaded from the IUCN Red List of Threatened Species www.iucnredlist.org/resources/spatial-data-download; accessed on 11 March 2024) and from Bird Life International (<http://datazone.birdlife.org/species/>

[requestdis](#); accessed on 11 March 2024) for the birds, and the area of each species range was calculated in QGIS v. 3.34.2 [34]. We grouped species by order or class, following the groupings of the initial IUCN data set (Table 1), and we calculated the median area size for each group using R v.4.3.1 [35], as the median is less affected by outliers than the mean (Table 1). Here, we considered taxonomic relatedness as an appropriate basis for determining mapping resolution as ecology generally related to phylogenetic conservatism at the order level [36–38], noting that it does not apply to all groups, and that the absence of phylogenetic analyses in some taxa hides a greater variability than currently recognized [39]. Treating this median range size as a circle, we calculated the log (base ten) of the radius, which we recommend to be used as the minimum segment lengths for range maps for each respective taxonomic group. We recognize that no species has a circular range and that taking the radius of this hypothetical circle is arbitrary, but since species ranges do not follow geometric shapes, the circle is the simplest approximation as its properties are independent of the number of sides, and the log-transformed radius produces segment lengths that are small enough to be practical and catered to the typical range size for each species (Table 1). The log-transformed radius is a bridge between ecological relevance as it is based on the ability of individuals to disperse across their range and logistic models are better approximates of the relationship between dispersal distance and home range in species such as mammals [40] and fish [41], and also because of the ease of use by conservation practitioners. Creating range maps with these segment lengths, either by modifying outputs from models or by refining hand-drawn maps, preserves the integrity of the original area and shape. Further, it is also critical for range maps to be updated to accurately reflect contemporary occurrence records of species [42,43].

Table 1. List of median areas for taxonomic groups and recommended minimum segment length calculated using the proposed method with (*) indicating non-exhaustive data available from IUCN Red List (<https://www.iucnredlist.org/resources/spatial-data-download>; accessed on 31 December 2023). The columns show the transformation of the dataset. The hypothetical radius of the area is converted for 1 degree = 111 km, at the equator. This variable is used as the default to demonstrate the principle introduced here.

Taxonomic Rank		Median Area (Degrees Squared)	Hypothetical Radius of Area (in Degrees)	Hypothetical Radius of Area (in Kilometers)	Log Transformed (Minimum Recommended Length in Kilometers)
Chordata					
Class	Myxini (represented here by order Myxiniiformes)	8.4383	1.6391	181.9350	2.2599
Class	Chondrichthyes	48.3879	3.9250	435.6696	2.6392
Order	Carcharhiniiformes	52.0850	4.0721	452.0071	2.6551
	Chimaeriformes	48.3879	3.9250	435.6696	2.6392
	Heterodontiformes	22.9586	2.7036	300.0974	2.4773
	Hexanchiformes	43.8644	3.7370	414.8061	2.6178
	Lamniformes	47.7446	3.8988	432.7641	2.6363
	Myliobatiformes	48.7784	3.9408	437.4240	2.6409
	Orectolobiformes	48.6758	3.9366	436.9637	2.6404
	Pristophoriformes	20.3366	2.5445	282.4416	2.4509

Table 1. Cont.

Taxonomic Rank		Median Area (Degrees Squared)	Hypothetical Radius of Area (in Degrees)	Hypothetical Radius of Area (in Kilometers)	Log Transformed (Minimum Recommended Length in Kilometers)
Chordata					
	Rajiformes	51.5259	4.0502	449.5745	2.6528
	Rhinopristiformes	48.3879	3.9250	435.6696	2.6392
	Squaliformes	48.8001	3.9416	437.5216	2.6410
	Suantiniiformes	118.2569	6.1359	681.0865	2.8332
	Torpediniiformes	48.7784	3.9408	437.4240	2.6409
Class	Actinopterygii	4.6009	1.2103	134.3413	2.1282
Order	Acipenseriformes	4.5469	1.2032	133.5506	2.1256
	Albuliformes	4.5444	1.2028	133.5135	2.1255
	Anguilliformes	4.5191	1.1995	133.1423	2.1243
	Atheriniiformes	4.6589	1.2179	135.1857	2.1309
	Aulopiformes	802.1046	15.9802	1773.7994	3.2489
	Batrachoidiiformes	5.0541	1.2685	140.8026	2.1486
	Beloniformes	4.4782	1.1940	132.5388	2.1223
	Characiformes	4.6002	1.2102	134.3317	2.1282
	Clupeiformes	4.6794	1.2206	135.4825	2.1319
	Cypriniformes	4.5966	1.2097	134.2791	2.1280
	Cyprinodontiiformes	4.5132	1.1987	133.0546	2.1240
	Elopiformes	5.6376	1.3397	148.7085	2.1723
	Esociformes	4.6174	1.2124	134.5815	2.1290
	Gadiformes	4.0282	1.1325	125.7022	2.0993
Class	Amphibia	0.3919	0.3520	39.0720	1.5919
Order	Anura	0.3919	0.3530	39.1830	1.5931
	Caudata	0.3777	0.3460	38.4060	1.5844
	Gymnophiona	0.3979	0.3550	39.4050	1.5956
Class	Reptilia	1.7948	0.7550	83.8050	1.9233
Order	Crocodylia	1.6695	0.7291	80.9257	1.9081
	Rhynchocephalia	0.0472	0.1225	13.6018	1.1336
	Squamata	1.7948	0.7559	83.9071	1.9238
	Testudines	1.7936	0.7557	83.8799	1.9237
Class *	Aves	39.7234	3.5562	394.7412	2.5963
Class	Mammalia	15.6448	2.2318	247.7277	2.3940
Order	Afrosoricicida	15.6448	2.2318	247.7277	2.3940
	Artiodactyla	15.7282	2.2377	248.3870	2.3951
	Carnivore	15.7134	2.2367	248.2703	2.3949

Table 1. *Cont.*

Taxonomic Rank		Median Area (Degrees Squared)	Hypothetical Radius of Area (in Degrees)	Hypothetical Radius of Area (in Kilometers)	Log Transformed (Minimum Recommended Length in Kilometers)
Chordata					
	Chiroptera	15.6876	2.2348	248.0663	2.3946
	Cingulata	15.5347	2.2239	246.8542	2.3924
	Dasyuromorphia	15.7429	2.2388	248.5025	2.3953
	Dermoptera	21.6072	2.6228	291.1306	2.4641
	Didelphimorphia	15.3673	2.2119	245.5205	2.3901
	Diprotodontia	15.7032	2.2359	248.1891	2.3948
	Eulipotyphla	15.2060	2.2003	244.2284	2.3878
	Hyracoidea	17.7613	2.3780	263.9529	2.4215
	Lagomorpha	15.4944	2.2210	246.5336	2.3919
	Macroscelidea	16.7496	2.3092	256.3250	2.4088
	Microbiotheria	14.5986	2.1559	239.3013	2.3789
	Monotremata	13.8485	2.0997	233.0720	2.3675
	Notoryctemorphia	61.1990	4.4141	489.9607	2.6902
	Paucituberculata	15.3101	2.2078	245.0634	2.3893
	Peramelemorphia	16.7496	2.3092	256.3250	2.4088
	Perissodactyla	15.4675	2.2191	246.3199	2.3915
	Pholidota	16.0427	2.2600	250.8579	2.3994
	Pilosa	15.4721	2.2194	246.3560	2.3916
	Primate	15.6448	2.2318	247.7277	2.3940
	Rodentia	15.6448	2.2318	247.7277	2.3940
	Scandentia	15.2942	2.2066	244.9363	2.3891
	Sirenia	16.3585	2.2821	253.3149	2.4037
	Tubulidentata	1612.0845	22.6548	2514.6811	3.4005
Non-Chordata					
Class	Hydrozoa (represented here by order Milleporina)	131.1314	6.4612	717.1932	2.8556
Class	Anthozoa	677.2486	14.6839	1629.9079	3.2122
Order	Alcyonacea	1605.5327	22.6087	2509.5658	3.3996
	Helioporacea	1591.8791	22.5124	2498.8722	3.3977
	Scleractinia	677.2486	14.6839	1629.9079	3.2122
Class	Malacastroca (represented here by order Decapoda)	1.8907	0.7759	86.1203	1.9351
Class	Insecta represented here by order Odonata)	0.7615	0.4924	54.6547	1.7376

Table 1. Cont.

Taxonomic Rank		Median Area (Degrees Squared)	Hypothetical Radius of Area (in Degrees)	Hypothetical Radius of Area (in Kilometers)	Log Transformed (Minimum Recommended Length in Kilometers)
Chordata					
Class	Gastropoda	3.1816	1.0064	111.7143	2.0481
Order	Allogastropoda	3.6631	1.0799	119.8703	2.0787
	Architaenioglossa	3.2495	1.0171	112.9015	2.0527
	Cycloneritida	4.2509	1.1633	129.1310	2.1110
	Ellobiida	3.1860	1.0071	111.7929	2.0484
	Hygrophila	3.2123	1.0113	112.2526	2.0502
	Hypogastropoda	75.3638	4.8983	543.7137	2.7354
	Lepetellida	47.1304	3.8736	429.9713	2.6334
	Littorinimorpha	3.1816	1.0064	111.7143	2.0481
	Neogastropoda	3.4591	1.0494	116.4853	2.0663
	Pylopulmonata	3.5796	1.0675	118.4970	2.0737
	Sorbeoconcha	3.3398	1.0312	114.4596	2.0587
	Stylommatophora	14.5342	2.1511	238.7726	2.3780
Class	Bivalvia	25.0300	2.8229	313.3427	2.4960
Order	Adapedonta	3.0543	0.9861	109.4572	2.0392
	Arcidae	54.4780	4.1646	462.2743	2.6649
	Cardiida	38.8211	3.5156	390.2321	2.5913
	Mytilida	23.3425	2.7261	302.5957	2.4809
	Ostreidae	76.8233	4.9455	548.9535	2.7395
	Unionida	25.0300	2.8229	313.3427	2.4960
	Venerida	23.8158	2.7536	305.6480	2.4852
All phyla pooled together		4.7769	1.2330	136.8630	2.1363

2.2. Demonstration of the Recommendations

To demonstrate the utility of our recommendation, in opposition with demonstrating it for all species, we selected two unrelated example species with dramatically different range sizes (Table 2). The first is the Confusing Rocket Frog, *Ectopoglossus confusus*, a species of amphibian endemic to Ecuador with only seven reported localities [44–46]. The second is the Cherry-eye Sprite, *Pseudagrion sublacteum*, a dragonfly species found across much of Africa and parts of west Asia [47]. For both species, we used the existing IUCN Red List of Threatened Species range maps, which generally had non-realistic looking shapes similar to model outputs, as a baseline [47,48]. We then created altered versions using our recommended minimum segment length of 1.59 km for *E. confusus* (order Anura) and 1.74 km for *P. sublacteum* (order Odonata) by either locking the size segment length when digitally drawing polygons or by using the simplify polygon tool in ArcGIS Pro v. 10.6. Altered polygons were also drawn to encompass existing locality records (GBIF.org, DOI: 10.15468/dl.rpma26; accessed on 11 March 2024; [44–46]).

Table 2. Evaluation of different range delineation techniques for two example species. Higher values of fractal dimensions indicate more complex shapes. Sensitivity indicates the proportion of occurrence records within 1 km of the depicted range.

Range Delineation Method	<i>Ectopoglossus confusus</i>		<i>Pseudagrion sublactum</i>	
	Fractal Dimension D	Sensitivity	Fractal Dimension D	Sensitivity
Political	1.33	7/7	1.37	586/586
Model	1.40	5/7	N/A	N/A
MCP	1.13	7/7	1.18	540/586
Buffered MCP	1.24	7/7	1.19	586/586
IUCN	1.32	7/7	1.39	586/586
IUCN revised with recommend minimum segment length	1.26	7/7	1.35	586/586
IUCN revised with 5 km minimum segment length	1.28	7/7	1.34	586/586
IUCN revised with 10 km minimum segment length	1.24	7/7	1.33	586/586

We then compared these maps with several other possible mapping techniques for these two species. First, we created political boundary representations by selecting administrative boundaries with existing occurrence records. For *E. confusus*, which has a small range, we selected the cantons within Ecuador (<https://data.humdata.org/dataset/cod-ab-ecu>; accessed on 11 March 2024), while for *P. sublactum*, which has a continental-sized range, we used country boundaries (<https://public.opendatasoft.com/explore/dataset/world-administrative-boundaries/export/>; accessed on 11 March 2024). We also made minimum convex polygons (MCPs) around the existing locality records for both species and buffered them by 0.1 degrees as MCPs are another common, though crude, way of delineating ranges [49]. Additionally, we incorporated an existing BIOCLIM model binary range output for *E. confusus* for comparison [46]. Lastly, we revised the IUCN maps using the same method as our recommended segment length but with segments of five and ten kilometers instead.

We evaluated the various mapping methods for our two example species using two metrics. First, to evaluate sensitivity, we calculated the proportion of existing locality records that were within one kilometer of each possible range polygon as an approximate sensitivity score in QGIS v. 3.34.2 [34] using occurrence data from the literature for *E. confusus* [44–46] and from GBIF for *P. sublactum* (GBIF.org, DOI: 10.15468/dl.rpma26; accessed on 11 March 2024). We recognize there certainly are locations where these species exist but have not been recorded that this sensitivity approximation is unable to account for, but we consider it critical for range maps to at least encompass known localities. Second, to evaluate the complexity of the resulting range shapes [50], we calculated the fractal dimension D of the polygons, which has values ranging from one (indicating the polygon is very regular) to two (indicating the polygon is very complex), using the box count method in the Minkowski Dimension Calculator QGIS plug-in [51]. For range representations with multiple disconnected shapes, all the fractal dimension values were averaged, except for the model and IUCN representations of *E. confusus*, where due to the presence of many small shapes only the fractal dimensions of the five shapes with the largest area were averaged.

3. Results

Our results show that the recommended segment length based on the median area calculation of the species (Figure 2, Table 1) varies between 1 and 3.40 km, with the least recommended segment value of 1.13 km for the reptilian order Rhynchocephalia and the maximum of 3.40 km for the mammalian order Tubulidentata (Table 1). Among all the animal orders, 93% have a recommended length below three kilometers. Sensitivity values for the *Ectopoglossus confusus* maps were 71.4% (5 out of 7 location records that are encompassed by the range shape) for the model output and 100% for all other representations (Figure 3). Polygon complexity for *E. confusus* varied between 1.13 for the MCP to 1.40 for the model output, with our recommended segment value having a score of 1.26 (Figure 3). Sensitivity values for the *Pseudagrion sublactum* maps were 92.2% (540/586) for the current IUCN range representation and 100% for all others (Figure 4). Fractal dimension scores for *P. sublactum* ranged from 1.18 for the MCP range to 1.39 for the IUCN range, with our recommended segment length map having a score of 1.35 (Figure 4).

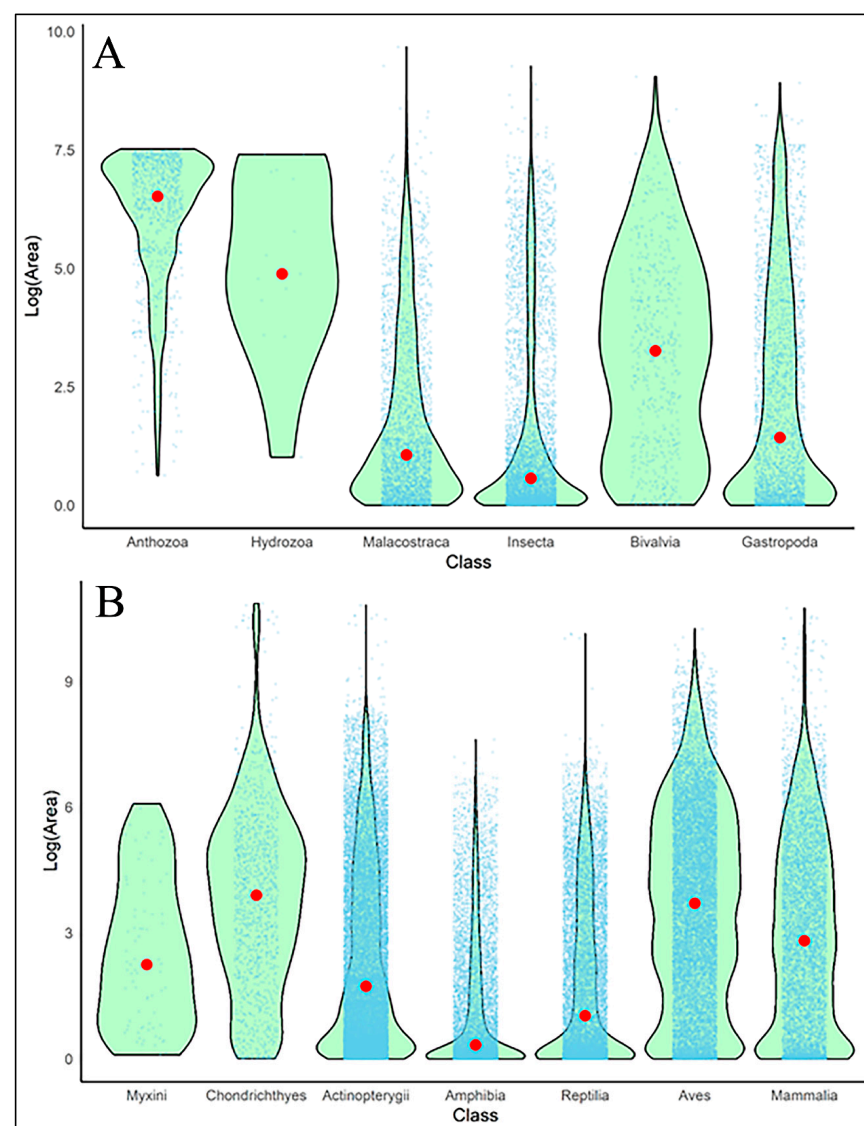


Figure 2. Violin plots of the area for each class under phylum Cnidaria, Arthropoda, Mollusca (A) and phylum Chordata (B). The data for the area is in square degree units and has been log transformed to rescale due to significant variation in the range of areas within each class. The median points are indicated in red.

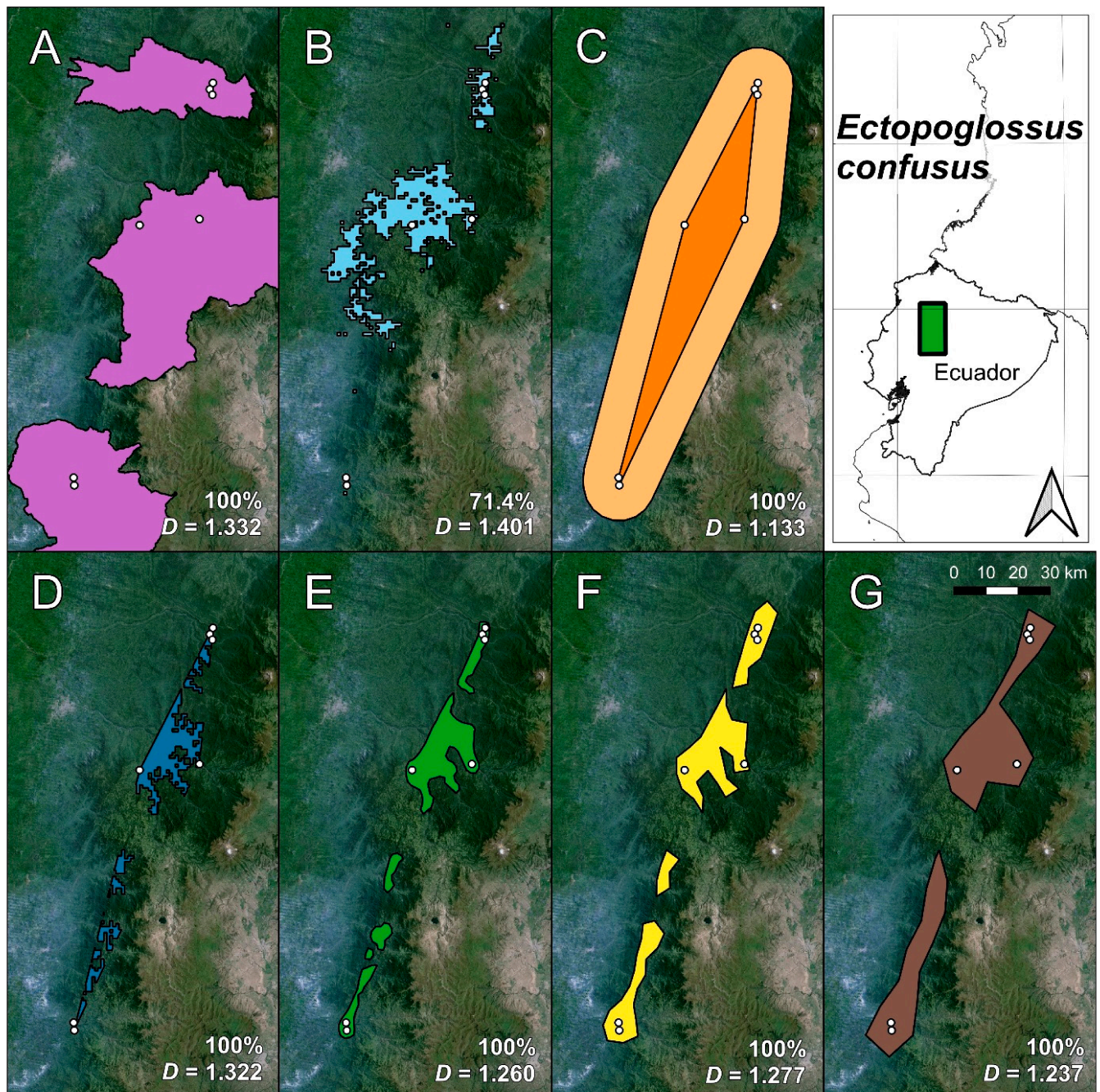


Figure 3. Range representations of the Confusing Rocket Frog, *Ectopoglossus confusus*. Locality records are shown with dots [45,46,48]. For each individual representation, the sensitivity score (proportion of locality records within 1 km of the drawn range) and fractal dimension (with values ranging from 1 to 2 and higher values indicating more complexity) are shown in the bottom right. Maps are as follows: (A) the cantons of Ecuador with known species records; (B) a BIOCLIM model output of the species [46]; (C) a minimum convex polygon drawn around the known records with a 0.1 degree buffer added; (D) the IUCN Red List of Threatened Species published range [48]; (E) the IUCN range re-drawn with our recommended minimum segment length of 1.59 km; (F) the IUCN range re-drawn with minimum segment lengths of 5 km; (G) the IUCN range re-drawn with minimum segment lengths of 10 km. (Satellite imagery: Google 2024 TerraMetrics).

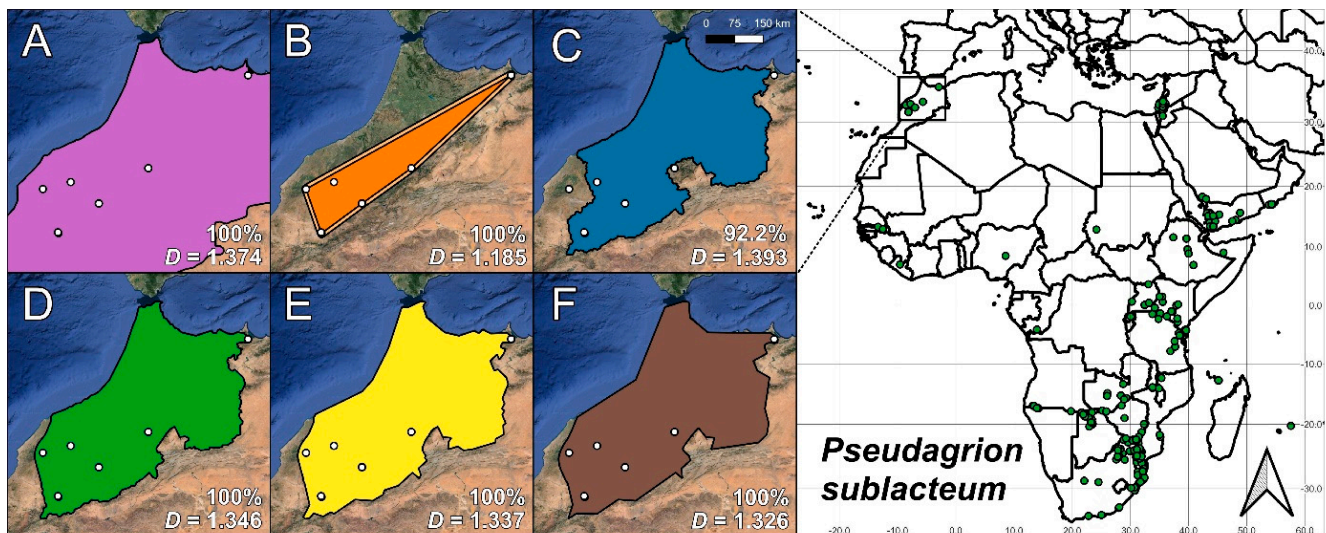


Figure 4. Range representations of the Cherry-eye Sprite, *Pseudagrion sublacteum*, cropped here to show only a portion of the range in Morocco. Locality records are shown with dots (GBIF.org, DOI: 10.15468/dl.rpma26; accessed on 11 March 2024). For each individual representation, the accuracy score (proportion of locality records within 1 km of the drawn range) and fractal dimension (with values ranging from 1 to 2 and higher values indicating more complexity) are shown in the bottom right. Maps are as follows: (A) countries with known species records; (B) a minimum convex polygon drawn around the known records with a 0.1 degree buffer added; (C) the IUCN Red List of Threatened Species published range [47]; (D) the IUCN range re-drawn with our recommended minimum segment length of 1.74 km; (E) the IUCN range re-drawn with minimum segment lengths of 5 km; (F) the IUCN range re-drawn with minimum segment lengths of 10 km (Satellite imagery: Google 2024 TerraMetrics).

4. Discussion

In general, we advocate that a combination of presence points, model outputs, and expert knowledge should be used together to produce maps with a taxonomically adjusted minimum segment length to delineate range boundaries. In our two species examples (Figures 3 and 4), our method was more sensitive than existing IUCN range depictions and produced polygons that were of an appropriate intermediate complexity compared to the other methods, with fractal dimension scores simpler than the overly complex IUCN or model representations for these species but not as simple as the MCP representations. We recommend that administrative boundaries, except for those based on geographic features, not be used for species border delineation as they are biologically irrelevant. Our method is most easily implemented by setting the distance of line segments to equal the recommended segment length for a given taxa when digitally drawing range polygons, which can be accomplished by using Dynamic Constraints (in ArcGIS Pro) or the Advanced Digitizing toolbar (in QGIS). If one is starting with a highly complex polygon from a model output, we recommend using the Simplify tool in ArcGIS Pro, setting the simplification tolerance to the recommended segment length for the specific taxa and using the Douglas–Peucker algorithm.

Ecological niche models can be informative when created carefully, but should be used as guidance in the creation of range maps rather than directly converted into range maps [32,52,53]. In addition, the continuous outputs of models are more informative than a binary threshold used to categorize suitable and unsuitable habitat [52]. This makes models effective tools for guiding experts in the drawing of more precise maps. One of the common shortcomings of expert hand-drawn maps is that they tend to be very coarse [54]. Our recommended segment length is much smaller than the long arbitrary segments used in

so-called “blob maps”, but is feasible to implement given the precision of digital mapping tools and the rapidly increasing amounts of biodiversity data [55]. Finally, the segment recommended here has a general length that is biologically relevant [56] and allows for better comparison between species. For instance, the segment length recommended for amphibians is 1.5919 km, a length over which variables related to the presence of a species do not vary greatly, as exemplified by the variation in annual mean temperature suitable for the Sakhalin toad (*Bufo sachalinensis*), which decreases by 1.33 degrees Celsius per degree of latitude [57]. However, this standardization is equally pragmatic and made to be used by conservation practitioners, as range size could be compounded by habitat heterogeneity, dispersal ability, body size, habitat specialization, and landscape configuration, among others, to be representative of range boundaries. In addition, the spatial resolution and quality of occurrence data may also influence the appropriate mapping resolution. Similarly, the great variation in some of the taxonomic groups (Figure 2) highlights the absence of abundant research on these groups and the need to update the length of segments regularly to reflect advances in knowledge over time.

Our method can also be used for describing ranges for migrating species by focusing on time-restricted boundaries for particular life-history stages, such as breeding and non-breeding grounds. Similarly, we consider it appropriate for range maps, when relevant, to depict confirmed, suspected, and extirpated ranges separately. We recognize that, due to data limitations for many under-studied groups, our calculations of minimum segment lengths do not encompass all taxa. In these instances, we recommend the approximate segment lengths for a group that is taxonomically similar or has similar sized range areas to be substituted. In addition, the use of a circular model to determine the length of segments to build ranges is subject to over-estimates in the case of linear (e.g., stream obligate species) or highly fragmented ranges. Sensitivity analyses based on better fitting geometric models could resolve this issue. However, other geometric models would introduce complexity and difficulty of use, which might make a global unified method difficult to be picked up by conservation managers that do not have access to the same resources as academics.

Range sizes are generally correlated with rarity and threat level, thus highlighting the need to better understand the distribution of species for conservation planning [54]. This is especially true for species impacted by habitat loss and climate change, with both threats having long-lasting effects [58]. As a result of the increasing impact of human activities working in synergy with climate warming, there have already been considerable changes in distribution for many organisms, and local extirpations caused by habitat loss or climate change can only be documented with sufficient prior knowledge of distributions [59–61]. Linking range loss and climate change with the life history and habitat requirements of species [62] will aid in determining which areas should be consolidated through protection to maintain the current extent of ranges. It is important to expand conservation to regions that are beyond the current network of protected areas and not overlook places that are not traditionally considered biodiversity hotspots [63].

Data harvested online from global databases such as the Global Biodiversity Database (GBIF; www.gbif.org) or the Ocean Biodiversity Information System (OBIS; www.obis.org) can be used for a wide variety of uses and can provide important baseline information [64] which can be augmented with targeted survey efforts for species or taxonomic groups [65,66]. This need for ad hoc data collection is especially salient for lesser-known groups, such as invertebrates or less studied vertebrates, where Wallacean shortfalls can skew median range size calculations because of the absence of representative data on distribution. In this case, species distribution model outputs often indicate suitable habitat in areas without records, and while these may represent false positives they could also

represent undiscovered populations and opportunities to improve the knowledge of a species range [67].

5. Conclusions

Wildlife conservation is becoming increasingly visible globally, but efforts remain heterogeneous. The boundaries of species' range are typically political, hand-drawn, or the result of ecological niche model outputs. This diversity of methods complicates comparisons, and each has its own weaknesses: political boundaries are typically artificial, hand-drawn maps are often imprecise, and ecological niche model outputs tend to be unrealistic. In this study we proposed a taxonomically adjusted and harmonized approach that combines the output of ecological niche models with the expert hand-drawn approach, using a minimum segment length relevant to the focal taxonomic unit, with the segments for most taxa ranging between two and three kilometers. Our approach offers an appropriate degree of precision and will allow for better, more standardized range delineations. We hope that our recommendations can be adopted, or further developed, by recognized organizations providing range maps for species, such as the IUCN Red List of Threatened Species, and by more localized conservation efforts. This work is meant to pragmatically advance conservation efforts worldwide by developing an approach that can be implemented across taxa and species in an attempt to mitigate conservation challenges.

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