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Global Distribution of Crocodilians Revealed by Citizen Scientists

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***Abstract.*—The conservation of crocodilians requires collaborative efforts on data collection, such as alliances between scientists and citizens. Citizen science emerges as an effective tool, engaging a larger audience than conventional scientific data collection methods. We compiled data of crocodilians recorded by citizen scientists through the iNaturalist platform on a global scale to evaluate the number of observations of crocodilians across families, genera, and species, geographic distribution and the number of observations and users of iNaturalist over time. The final dataset comprised 63,530 observations from 21,885 observers, documenting 27 crocodilian species from nine genera and three families. Notably, the American Alligator (*Alligator mississippiensis*; n = 40,473; 64%) and the American Crocodile (*Crocodylus acutus*; n = 6,209; 10%) had the highest number of observations. Regarding conservation status, 11 (41%) species are threatened with extinction according to the International Union for Conservation of Nature, with seven (26%) classified on the Red List as Critically Endangered (CR), one (4%) as Endangered (EN) and three (11%) as Vulnerable (VU). The dataset included observations from 87 countries, with the USA (n = 41,824; 66%) contributing the highest number of observations and Brazil and Colombia (n = 6 species; 22%, each) contributing the highest number of species. Temporal analysis revealed that the number of observations increased in 2016 (n = 2,365) and reached a mean of 7,758 observations per year from 2016 to 2022. Our study demonstrated that data derived from citizen scientists provides valuable insights into the spatial and temporal distribution of crocodilians globally.**

Key Words.—crocodilian; citizen science; conservation status; crowdsourcing; open databases; public participation

Introduction

Citizen science, a collaborative effort between scientists and volunteers, plays a pivotal role in generating biodiversity data and addressing some scientific inquiries (Dickinson et al. 2012; Bonn et al. 2016). Studies demonstrate that data collection through citizen science can be as effective as collections conducted by specialists if all that is required is identification of species, which benefit from the involvement of a large community in generating scientific information (Koffler et al. 2021; Fontaine et al. 2022). Therefore, the application of citizen science has the potential to reduce gaps in our understanding of species distributions (Whittaker et al. 2001; Bini et al. 2006).

Citizen science has been employed in various scientific fields ranging from inventories and geographic distribution to population monitoring (Frigerio et al. 2018; Zocca et al. 2024). Citizen scientists have significantly contributed to assessing biological and ecological aspects of various invertebrate and vertebrate species, including birds (Sullivan et al. 2009; Alexandrino et al. 2022), corals (Marshall et al. 2012), sharks (Vianna et al. 2014), bees (Domroese and Johnson 2017; Koffler et al. 2021), anurans (Rowley et al. 2019; Forti and Szabo 2023), and reptiles (Maharani et al. 2022). Given the increasing number of species in the world threatened with extinction, citizen science emerges as a powerful tool to engage local communities and tourists in collecting data on the distribution and abundance of crocodilians (crocodiles, alligators, and gharials).

Globally, there are 27 recognized species of crocodiles, with 11 of them classified as threatened with extinction (International Union for Conservation of Nature [IUCN] 2023; http://www.reptile-database.org). Caimans (three genera) are endemic to South and Central America, while alligators (*Alligator* sp.) are endemic to the USA and China. Crocodiles

(three genera) have a broader distribution, spanning the Americas, Africa, Asia, and Oceania. Gharials (*Tomistoma gangeticus*) are found solely in India, confined to small and threatened populations (Maddok 2010). These animals hold ecological value as indicators of ecosystem health, ecosystem engineers, and top predators in food chains contributing to energy flow and nutrient cycles in aquatic and terrestrial ecosystems (Somaweera et al. 2020).

The iNaturalist platform (https://www.inaturalist.org), with approximately 3.2 million citizen scientists, facilitates collaborative and participatory efforts in documenting global biodiversity observations. Users can submit photographic and audio records, including geographic locations and taxonomic identifications. Several crocodilian-related groups on iNaturalist, such as the Herpetological Association of Zimbabwe, Crocodiles of the World, Crocodilianos do Brasil, UC Jacaré Serra dos Pintos, Jacarés da Região Metropolitana de Manaus, and Projeto Caiman - Jacarés da Mata Atlântica, offer the potential to integrate data collection with education and environmental awareness, providing societal and biodiversity benefits (Frigerio et al. 2018). We used citizen science data from the iNaturalist platform, encompassing all existing crocodilian species worldwide, to understand their geographic and temporal distribution.

Materials and Methods

We systematically acquired observations and associated metadata for all 27 crocodilian species accessible on the iNaturalist platform (https://www.inaturalist.org) from the inception of the platform (1996) through 31 December 2022. A comprehensive database was curated, incorporating metadata from each observation, encompassing relevant variables provided by citizen scientists, such as location, date, geographic coordinates, species identification, and other user information. We excluded species recorded in captivity (e.g., labs and zoos) due to the unknown data provenance of these animals. Taxonomic classification follows the Reptile Database (http://www.reptile-database.org).

The first dataset comprised 65,014 crocodilian observations, categorized into three distinct quality levels (Research Grade, Needs Identification, and Casual Observations). In iNaturalist, a record is Research Grade status when the iNaturalist community, involving a minimum of three collaborators and/or experts, reaches a consensus on species identification. Conversely, records labeled as Needs Identification denote cases where species identification lacks consensus within the iNaturalist community, primarily composed of professionals in the biological sciences. Casual Observations denote the absence of essential geographic or temporal data. For the analysis, we only considered the 63,530 (98%) records classified as Research Grade, indicating a consensus on species identification within the iNaturalist community.

We analyzed the absolute and relative numbers of families, genera, and species of crocodilians included in the final dataset. To discern potential biases and identify gaps in the representation of crocodilians, we also evaluated the number of observations over time (from the first observation in 1969 to 2022), the number of users, the geographical distribution of the observations, and the conservation status of each recorded species (based on IUCN 2023). Furthermore, we analyzed the spatial distribution of the observed species in QGis version 3.22.4 (http://qgis.osgeo.org/). We employed a heatmap plugin to generate a Kernel Density Estimation map of crocodilian locations. The color scale employed a base 10 logarithmic function, ensuring a smooth color gradient for enhanced visual interpretation of spatial distribution patterns.

Results

Our final dataset comprised 65,014 observations provided by 21,885 observers, representing 27 species of crocodilians across nine genera and three families (Appendix Table). The dataset had 63,530 observations (98%) as Research Grade, indicating data suitable for publication, 414 observations (< 1%) as Needs Identification requiring species identification, and 1,070 observations (2%) as "Casual" attributed to the absence of essential geographic or temporal data. Alligatoridae (n = 47,248 observations; 74%; eight species; 30%) and Crocodylidae (n = 16,089 observations; 25%; 18 species; 67%) had the highest number of observations and species. At the genus level, *Alligator* (n = 41,087 observations; 65%; two species; 7%) had the highest number of observations. The greatest number of species (12; 44% of total) were for the genus *Crocodylus* (n = 15,956 observations; 25%). At the species level, *Alligator mississippiensis* (n = 40,473 observations; 64%) and *Crocodylus acutus* (n = 6,209 observations; 10%) had the highest number of observations, whereas four

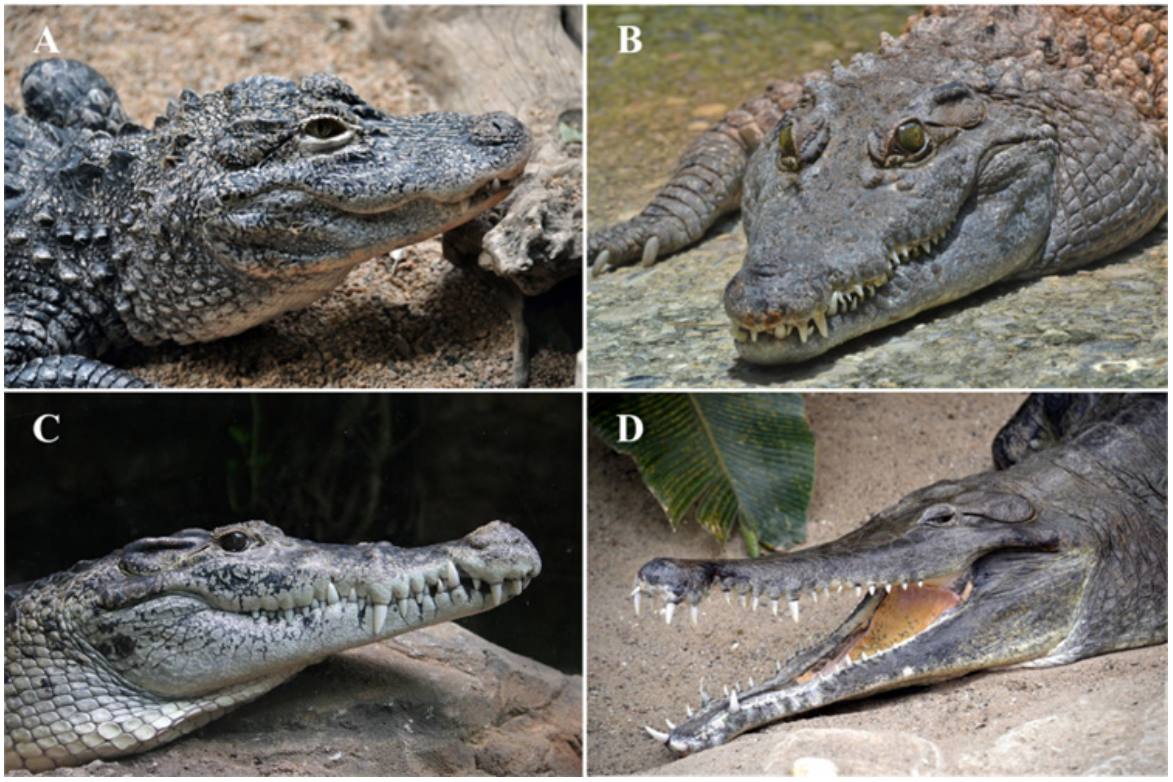

Figure 1. Crocodilian species with fewer than 10 observations on the iNaturalist platform: (A) Chinese Alligator (*Alligator sinensis*); (B) Philippine Crocodile (*Crocodylus mindorensis*); (C) New Guinea Crocodile (*Crocodylus novaeguineae*); and (D) African Slender-Snouted Crocodile (*Mecistops cataphractus*). (A photographed by Oriol Gascón i Cabestany, B by Jonathan Zimmermann, C by Wilfried Berns, and D by Tim Strater).

(15%) species had fewer than 10 observations each (Appendix Table; Fig. 1).

Regarding conservation status, 11 (41%) species are threatened with extinction according to the IUCN Red List (IUCN 2023), with seven (26%) classified as Critically Endangered (CR), one (4%) as Endangered (EN), and three (11%) as Vulnerable (VU). Twelve species (44%) are Least Concern (LC) and four (15%) species remain unassessed by the IUCN. *Gavialis gangeticus* (n = 193 observations; < 1%) had the highest number of observations within species listed as CR, while *C. acutus* (n = 6,209 observations; 25%) had the highest number of observations within species listed as VU.

The dataset encompassed observations from 87 countries (Fig. 2). The highest number of observations for a country was for the USA (n = 41,824 observations; 66%; Fig. 3), followed by Mexico (n = 4,373 observations; 7%), and Costa Rica (n = 3,180 observations; 5%). Brazil, Colombia, and Bolivia reported the highest number of species (six; 22% each), followed by Ecuador and Peru (five; 18% each). The Nile Crocodile (*Crocodylus niloticus*) was the most widely distributed species, being reported from 23 countries.

The first crocodilian observation on iNaturalist was in 1969. From 1969 to 2009, the mean number of observations annually was 80. From 2009 to 2016, the mean number of observations was 1,183 per year. The number of observations increased in 2016 to 2,365 and reached a mean of 7,758 observations per year through 2022 (Fig.4).

Discussion

Distributional and temporal data available in iNaturalist can be useful to scientists because data are compiled and openly available, which can benefit future studies about distribution modeling, geographical extension, comparison to scientific records, etc. Our survey determined that all 27 recognized crocodilian species have been reported on iNaturalist (http://www.reptile-database.org). The efficacy of recording all crocodilian species can be attributed to various factors, including the human fascination with top predators, their conspicuousness due to frequent presence near water bodies, their immobility at rest, their large body size, and the

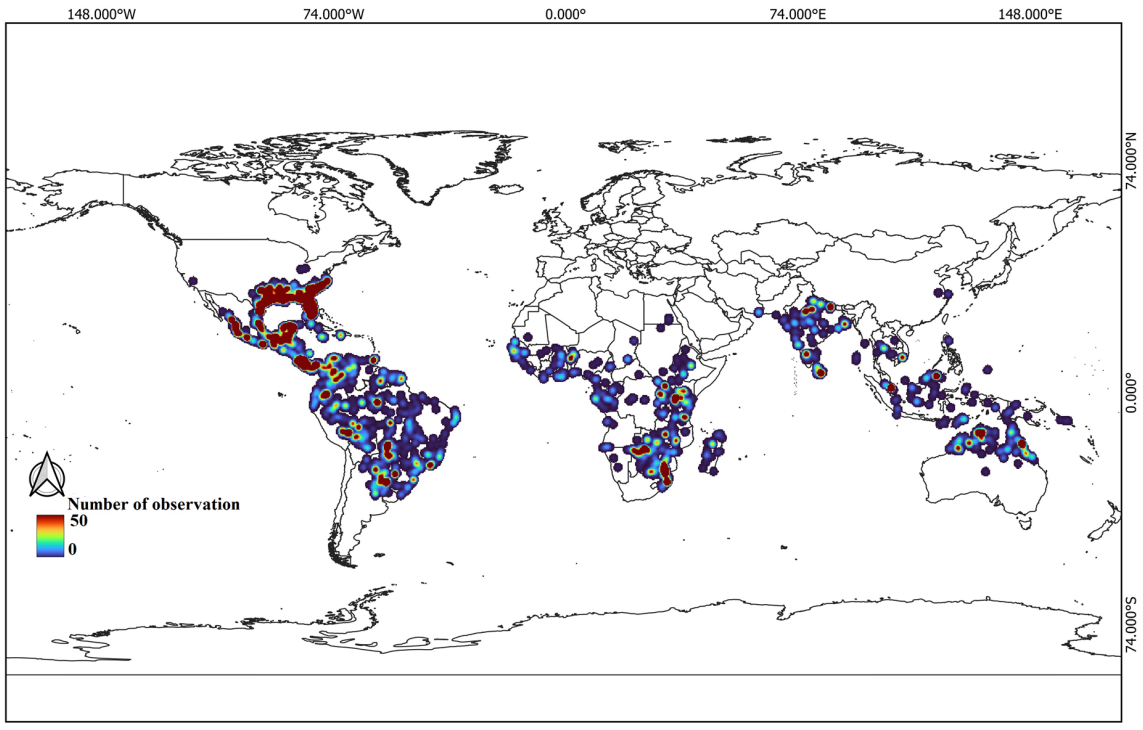

Figure 2. A Kernel Density Estimation map of the number of observations of crocodilians made by citizen scientists around the world.

widespread availability of cellphones, which allow for easy capture of photographs (Ross 1998; Grigg and Kirshner 2015). In contrast, studies focusing on smaller taxa with limited geographic distribution demonstrated comparatively lower efficiency in recording species (Brown and Williams 2019; Di Cecco et al. 2021; Fontaine et al. 2022; Zocca et al. 2024). Therefore, iNaturalist is emerging as an increasingly effective survey method for crocodilians, particularly for species inventory and spatial and temporal ecology (Maharani et al. 2022).

Alligator mississippiensis exhibited the highest number of observations (64%), greatly surpassing the second most recorded species, *C. acutus* (10%). *Alligator mississippiensis* is found in coastal regions of the southeastern USA, and it is the most studied crocodilian species (Joanen and McNease 1987; Mazzotti and Brandt 1994). Most observations of *A. mississippiensis* were concentrated in the Everglades National Park, USA, a renowned destination for tourists and professional photographers, aligns with the accumulation of over 40,000 observations of the *A. mississippiensis*. This high number of observations can also be attributed to the widespread popularity of citizen science in the USA, a practice embraced and encouraged across diverse age groups (Shirk et al. 2012). The synergy of these factors underscores the significance of *A. mississippiensis* as a focal point for

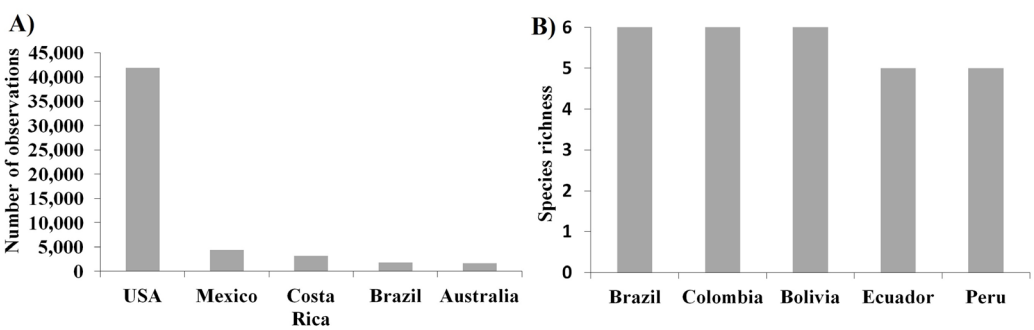

Figure 3. Number of observations and species of crocodilians made by citizen scientists showing countries with the highest numbers: (A) number of observations; (B) species richness of crocodilians.

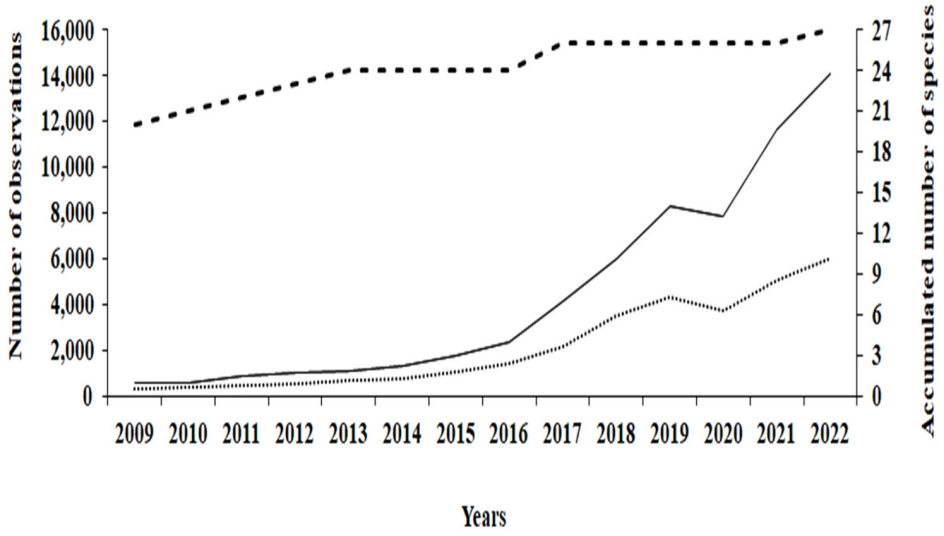

Figure 4. Number of observations (continuous line), number of species reported (dashed line), and number of citizen scientists that reported the observations (spaced dotted line) from 1969 to 2022.

citizen science initiatives and emphasizes the broader cultural acceptance and engagement in scientific observation practices in the U.S.

All 11 species globally classified as Threatened by the IUCN were reported by citizen scientists. *Gavialis gangeticus* had the highest number of observations among Critically Endangered (CR) species. It is important to highlight the substantial recovery of this species from the brink of extinction in recent decades, attributed to studies and investments in egg incubation and initial rearing of hatchlings in captivity (Magnussun 1986; Maddock 2010). The Chinese Alligator (*Alligator sinensis*), Philippine Crocodile (*Crocodylus mindorensis*), New Guinea Crocodile (*C. novaeguineae*), and African Slender-snouted Crocodile (*Mecistops cataphractus*), however, were represented on iNaturalist with fewer than 10 reports, potentially influenced by limited geographic distribution, water pollution, illegal trade, and hunting (Ortega 1998; Hilton-Taylor 2000; McKinley et al. 2017; IUCN 2023). These findings highlight the critical need for increased conservation efforts for these lesser-documented and threatened crocodilian species.

Four crocodilian species remain unevaluated by the IUCN, primarily due to insufficient data or limited research, posing challenges to accurate conservation status assessments. The comprehensive assessment of each species demands considerable time, expertise, and resources (Allouche 2006; IUCN 2023). The IUCN relies on contributions from experts and organizations, and resource constraints can impede the assessment process. Studies indicate that more than half of the species lacking evaluations or with data deficiencies may be listed in threatened categories (Borgelt et al. 2022). On the iNaturalist platform, the West African Crocodile (*Crocodylus suchus*) had 306 observations, the Central African Slender-snout Crocodile (*Mecistops leptorhynchus*) had 55 observations, the Hall's New Guinea Crocodile (*Crocodylus*) had 13 observations, and the Osborn's Dwarf Crocodile (*Osteolaemus osborni*) had 11 observations, highlighting the potential of citizen science in providing geographic records for improving conservation assessments of these species.

Citizen scientists have contributed to observations of crocodilians in 87 countries on the iNaturalist platform. The USA (66%) and Mexico (7%) had the highest number of observations of crocodilians. The robust tradition of involving the public in citizen science projects in the U.S., coupled with a history of civic participation, a large population, geographic diversity, the use of technology and social media, as well as the high abundance of *A. mississippiensis*, positions the country as a significant driver of public engagement in scientific research projects (Shirk et al. 2012; Haklay et al. 2016). This fact may also explain the highest number of *A. mississippiensis* observations. Unsurprisingly, in terms of species richness that is found on iNaturalist, tropical countries with aquatic ecosystems stand out with Brazil and Colombia being particularly notable for holding the highest crocodilian richness, each with six species (Medem 1983; Churio 2006, 2015; Costa

and Bérnils 2018). By facilitating active participation in data collection, citizen science plays an important role in comprehending species distribution (Cooper et al. 2007; Silvertown 2009; Bonney et al. 2014; McKinley et al. 2017).

The number of species observations and the number of citizen scientists on iNaturalist experienced a substantial increase in 2016 and 2017. Since the platform was created in 2008, the number of users and observations has shown significant growth in this short time span. This trend may be attributed to the widespread accessibility and use of smartphones and mobile devices, facilitating easier documentation of these animals. Additionally, the rise in popularity of ecotourism, providing opportunities for direct interaction with natural environments, is likely to have contributed to the observed increase in record numbers (Sienknecht et al. 2018; Schaffer and Tham 2019; Ortega-Álvarez and Calderón-Parra 2021).

In summary, this study has yielded a large amount of spatial and temporal data of global crocodilians; however, it is essential to acknowledge certain limitations of citizen science data on the iNaturalist platform, including variations in photo quality, potential geographic sampling biases, and the need for scientific validation (Brenton 2021). We advocate for the establishment of a dedicated CrocDay initiative, encouraging citizen scientists to document wild crocodiles and upload their observations to iNaturalist. Therefore, the use of iNaturalist emerges as a valuable tool for augmenting scientific data on geographic and temporal records, providing crucial support for research and conservation efforts (Cooper et al. 2007; Forti and Szabo 2023; Zocca et al. 2024).

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Appendix Table. The number (n) and percentage (%) of iNaturalist observations of crocodilians worldwide. Also listed are the countries in which each species is found and their staus on the red List of the International Union for the Conservation of Nature (LC = Least Concern, NE = Near Endangered, VU = Vunerable, EN = Endangered, and CR = Critically Endangered).

Family/Species	Common Name	n (%)	Country	Status
Alligatoridae				
Alligator mississippiensis	American Alligator	40,473 (64%)	USA	LC
Alligator sinensis	Chinese Alligator	4 (< 1%)	China	CR
Caiman crocodilus	Common Caiman	3,502 (5%)	Bolivia, Brazil, Colombia, Costa Rica, Ecuador, El Salvador, French Guiana, Guatemala, Guyana, Honduras, Mexico, Nicaragua, Panama, Peru, Suriname, Trinidad and Tobago, USA , Venezuela	LC
Caiman latirostris	Broad-Snouted Caiman	884 (1%)	Argentina, Bolivia, Brazil, Paraguay, Uruguay	LC
Caiman yacare	Yacare Caiman	1,545 (2%)	Argentina, Bolivia, Brazil, Paraguay	LC
Melanosuchus niger	Black Caiman	444 (< 1%)	Bolivia, Brazil, Colombia, Ecuador, French Guiana, Guyana, Peru	LC
Paleosuchus palpebrosus	Dwarf Caiman	108 (< 1%)	Bolivia, Brazil, Colombia, Ecuador, French Guiana, Guyana, Peru	LC
Paleosuchus trigonatus	Schneider's Smooth-Fronted Caiman	288 (< 1%)	Bolivia, Brazil, Colombia, Ecuador, French Guiana, Guyana, Peru	LC
Crocodylidae				
Crocodylus acutus	American Crocodile	6,209 (10%)	Belize, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Peru, USA, Venezuela	VU
Crocodylus halli	Hall's New Guinea Crocodile	13 (< 1%)	Indonesia, Papua New Guinea	NE
Crocodylus intermedius	Orinoco Crocodile	23 (< 1%)	Colombia, Venezuela	CR
Crocodylus johnstoni	Freshwater Crocodile	379 (< 1%)	Australia	LC
Crocodylus mindorensis	Philippine Crocodile	4 (< 1%)	Philippines	CR
Crocodylus moreletii	Morelet's Crocodile	2,431 (4%)	Belize, Guatemala, Mexico	LC

Crocodylus niloticus	Nile Crocodile	3,360 (5%)	Angola, Botswana, Burundi, Democratic Republic of Congo, Egypt, Eswatini, Ethiopia, Gabon, Kenya, Madagascar, Malawi, Mozambique, Namibia, Republic of Congo, Rwanda, South Africa, Sudan, Tanzania, Uganda, Zambia, Zimbabwe	LC
Crocodylus novaeguineae	New Guinea Crocodile	1 (< 1%)	New Guinea	LC
Crocodylus palustris	Mugger Crocodile	861 (1%)	India, Iran, Nepal, Pakistan, Sri Lanka	VU
Crocodylus porosus	Saltwater Crocodile	2,250 (4%)	Australia, Bangladesh, Brunei, East Timor, India, Indonesia, Malaysia, Myanmar, Palau, Papua New Guinea, Philippines, Singapore, Sri Lanka.	LC
Crocodylus rhombifer	Cuban Crocodile	19 (< 1%)	Cuba	CR
Crocodylus siamensis	Siamese Crocodile	100 (< 1%)	Camboda, Laos, Thailand, Vietnam	CR
Crocodylus suchus	West African Crocodile	306 (< 1%)	Benin, Burkina Faso, Cameroon, Chad, Cote d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Mali, Mauritania, Niger, Nigeria, Republic of Congo, Senegal, Sierra Leone, Uganda	NE
Mecistops cataphractus	African Slender-Snouted Crocodile	5 (< 1%)	Cote d'Ivoire, Ghana, Sierra Leone	CR
Mecistops leptorhynchus	Central African Slender-Snouted Crocodile	55 (< 1%)	Central African Republic, Democratic Republic of the Congo, Gabon, Republic of the Congo	NE
Osteolaemus osborni	Osborn's Dwarf Crocodile	11 (< 1%)	Angola, Cameroon, Gabon, Republic of Congo	NE
Osteolaemus tetraspis	Dwarf Crocodile	49 (< 1%)	Benin, Cameroon, Cote d'Ivoire, Gabon, Ghana, Nigeria, Sierra Leone	VU
Tomistoma schlegelii	False Gharial	13 (< 1%)	Indonesia, Malaysia	EN
Gavialidae				
Gavialis gangeticus	Gharial	193 (<1%>	India, Nepal	CR