The suitability of census techniques for the management of threats to crocodilian populations

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Abstract

Crocodilians are important aquatic predators that serve as indicators of ecosystem integrity, but many species face anthropogenic pressures. Effective adaptive management of crocodilian populations depends on reliable population monitoring, but different census techniques vary in accuracy, precision, and operational constraints. A systematic literature review of 161 peer-reviewed studies (1970–2023) was conducted to identify reported threats, monitoring methods, study duration, limitations, and concluded population trends. Threats were categorised into nine classes and monitoring techniques into six broad groups. The most frequently reported threats were pollution and habitat degradation, hunting and poaching, and human-wildlife conflict. Monitoring remains dominated by spotlight surveys (54%), while UAV use remains limited (3%). Most studies were short-term and geographically clustered, and 70 studies did not conclude a population trend. In addition, to evaluate different survey methodology, night-time spotlight counts, crewed aerial surveys, and Uncrewed Aerial Vehicle (UAV) surveys were compared in the Olifants River Gorge (Kruger National Park, South Africa) and a 10 km reach below Loskop Dam using standardised effort metrics (person-hours per survey and per kilometre). UAV surveys required fewer person-hours per kilometre than spotlight surveys and recorded higher adult counts, while spotlight counts detected more juveniles. Crewed aerial surveys required the least effort but produced the lowest counts. No single technique provided an unbiased representation of demographics. Integrated, standardised, long-term monitoring frameworks incorporating UAV technology and complementary ground-based methods are necessary to improve detection reliability and support evidence-based crocodilian management.

Introduction

Freshwater ecosystems cover only a small proportion of Earth's surface, yet experience extinction rates approximately five times higher than those of terrestrial systems (Ricciardi & Rasmussen, 1999). Despite supporting high biodiversity, they face escalating pressures from climate change, invasive species, disease, algal blooms, hydropower expansion, emerging contaminants, microplastics, salinisation, and cumulative stressors (Reid et al., 2019; Slimani et al., 2022).

Crocodilians function as indicator species in tropical and subtropical freshwater systems across Africa, Asia, Australia, and the Americas (Somaweera et al., 2020). Their measurable responses to habitat alteration and management interventions make them useful for assessing ecosystem restoration, as demonstrated in the Florida Everglades (Mazzotti et al., 2009). Approximately 25% of crocodilian species are critically endangered, underscoring the need for effective conservation and adaptive management (Sawan et al., 2023).

Adaptive management depends on accurate, long-term census data to reduce uncertainty in decision-making (Nicol et al., 2022; Somaweera et al., 2020). Population estimates are affected by imperfect detection and methodological bias. Census techniques include night-time spotlight counts, diurnal surveys, crewed aerial counts, mark-recapture, and Uncrewed Aerial Vehicles (UAVs) (Calverley & Downs, 2014; Ezat et al., 2018). Night-time spotlight counts are widely used, but may overestimate smaller size classes and pose safety risks (Calverley & Downs, 2014; Combrink et al., 2011). Diurnal surveys can underestimate abundance (Panda et al., 2023). Aerial counts are costly and may under-detect juveniles (Wang et al., 2019). Mark-recapture studies are labour-intensive and risky (Ortiz et al., 2020). Across all different techniques, observer and visibility bias can compromise detection accuracy (Barão-Nóbrega et al., 2022; Cartagena-Otalvaro et al., 2020).

These limitations often result in short-term, event-driven studies rather than systematic long-term monitoring (Hauser et al., 2006), increasing the risk of misleading trend interpretation. The Nile crocodile die-off in the Olifants River Gorge illustrates how detection bias and methodological constraints complicate threat identification and management response (Ferreira & Pienaar, 2011). This study, therefore, aims to (1) identify global threats to crocodilian populations, (2) evaluate the strengths and limitations of census techniques, (3) assess the influence of study duration and spatial extent on trend interpretation, and (4) compare census approaches applied to the same populations in South Africa to inform improved monitoring strategies.

Methods

Systematic literature review

A systematic review was conducted to identify global threats to crocodilian populations and evaluate monitoring techniques. Searches were performed in Web of Science, Scopus, and Dimensions using Boolean combinations of terms related to crocodilians, population monitoring, and survey methods. Genetic, captive, nesting, and non-monitoring studies were excluded. Only peer-reviewed English-language articles were considered.

After duplicate removal in Mendeley and screening in Covidence, 161 studies were retained following PRISMA 2020 guidelines (Page et al., 2021). Titles, abstracts, and full texts were screened independently. The following data were extracted from each study: geographic region, species or family monitored, monitoring technique, study and survey duration, reported limitations, identified threats, and concluded population trends. Studies were grouped into six regions: South America, North America, Africa, India (including Nepal, Pakistan, Bangladesh, and Bhutan), Asia (China and Southeast Asia) and Australasia (including Indonesia and Papua New Guinea).

Threats were classified into nine categories: agriculture, climate change, dams, fishing practices, human-wildlife conflict, hunting/poaching, invasive species, pollution/habitat degradation, and urbanisation/human population growth. Population trends were categorised as range expansion, range contraction, population increase, population decrease, or combined range and population change. Monitoring techniques were grouped as night-time spotlight counts, diurnal counts, crewed aerial surveys, mark–recapture, UAV surveys, and other methods.

Study locations were georeferenced and mapped in QGIS, overlaid with global crocodilian distributions (IUCN, 2023). Study duration was classified into seven five-year intervals (0–5 years, 5-10 years,…,>30 years). Reported limitations were grouped into funding, permitting, safety, accessibility, and area extent. Data synthesis and descriptive analyses were conducted in Microsoft Excel and GIS software.

Comparing survey methods

Two South African river systems were used to compare census techniques applied to the same crocodile populations. The Olifants River Gorge in Kruger National Park and a 10 km reach of the Olifants River below Loskop Dam. Both systems have been surveyed using multiple methods, allowing direct comparison of detection rates, survey effort, and operational constraints.

Three techniques were evaluated: night-time spotlight counts, crewed aerial surveys, and Uncrewed Aerial Vehicle (UAV) surveys.

Spotlight counts followed known protocols (Hutton & Woolhouse, 1989) and were conducted between 19:00 and 00:00, using boats, vehicles, or foot surveys depending on accessibility. Crocodiles were detected via eye-shine and, where possible, size classes were estimated. At Loskop Dam, multiple observers independently counted individuals per section to assess precision, although inaccessible areas within sections limited the extent of spatial coverage. Crewed aerial surveys (Kruger National Park only) were conducted using fixed-wing aircraft flown at low altitude during daylight basking periods (Myburgh, 2021). This method enabled rapid coverage but reduced the

detection of smaller individuals. UAV surveys were conducted in both systems (Myburgh, 2021) using automated flight paths at approximately 100 m altitude during daytime basking periods. Imagery was processed to produce high-resolution orthomosaics using photogrammetric software and analysed in QGIS by multiple observers to assess precision.

Survey effort was standardised as total person-hours per survey and person-hours per kilometre surveyed, enabling direct comparison of efficiency and detection performance across methods despite differences in survey year and environmental conditions.

Loskop Dam surveys were conducted under University of Pretoria Animal Ethics approval (NAS318/2022) and Mpumalanga Tourism and Parks Agency permit (MPB.5855), with additional landowner permissions.

Results

Global threats

From the 161 reviewed studies, the most frequently reported threats to crocodilian populations were: Pollution and habitat degradation, hunting and poaching, and human–wildlife conflict. Secondary threats included dam construction, agriculture, invasive species, urbanisation, climate change, and fishing practices (Figure 1).

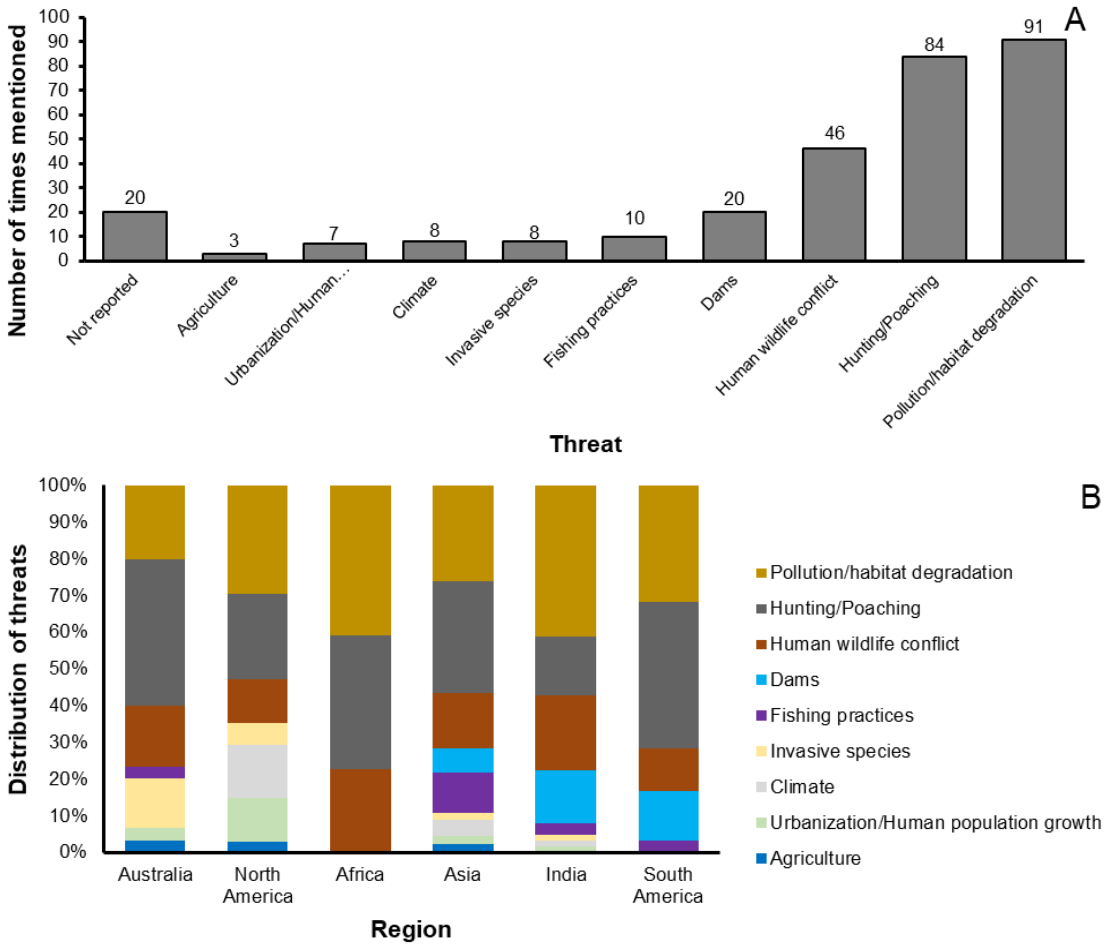


Figure 1. The threat categories concluded from the 161 published articles in the systematic literature review. A) The number of studies in which each of the threat categories have been concluded. B) The percentage of each threat category in each of the six regions.

Threat patterns varied among crocodilian families (Figure 2). Pollution and habitat degradation were particularly prominent in studies on Gavialidae, while hunting and poaching were common across Crocodylidae and Alligatoridae. Regional variation was observed during analysis, with dam construction and hydrological alteration more frequently reported in South America and the Indian subcontinent, while human–wildlife conflict was especially prominent in Africa and parts of Asia.

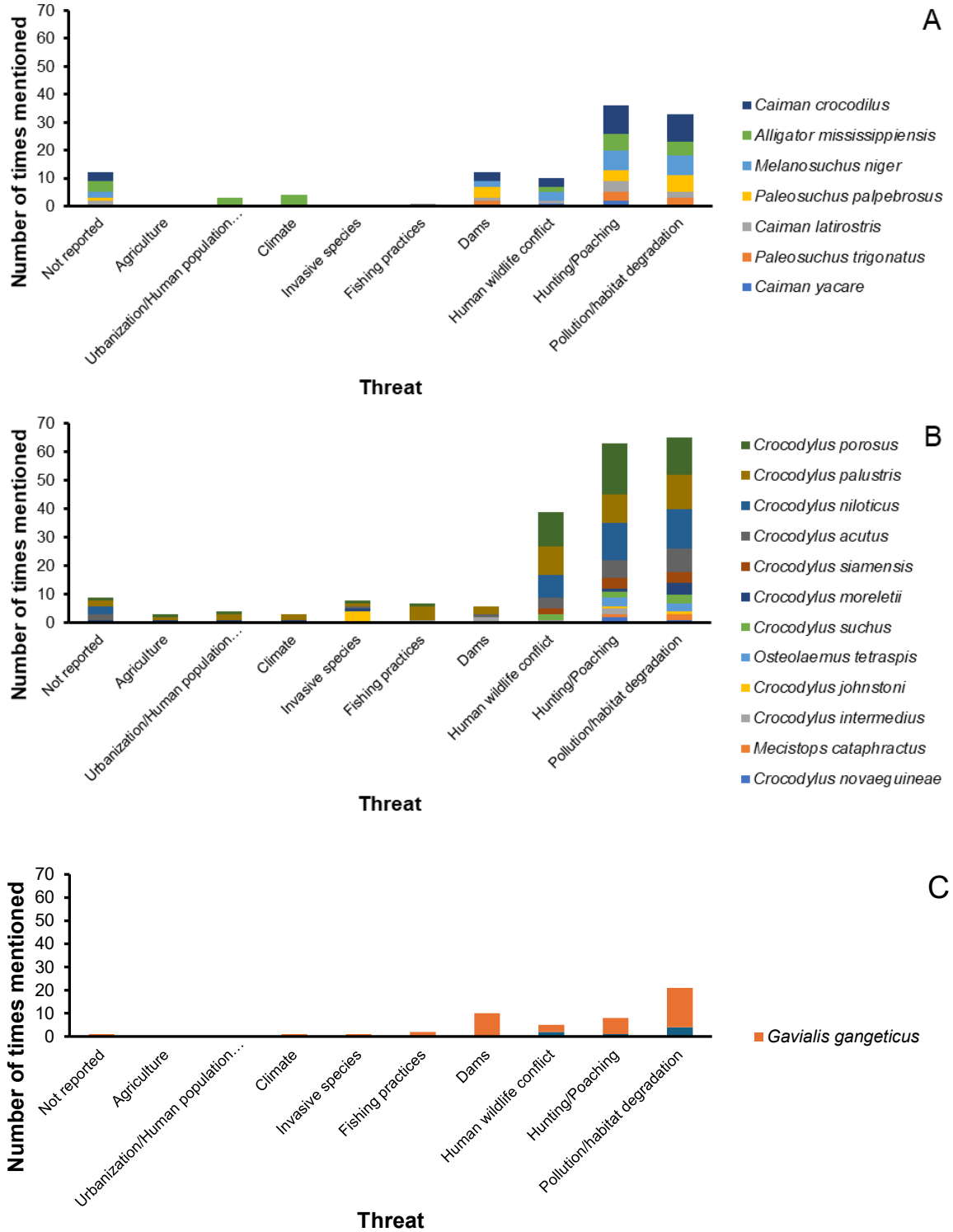


Figure 2. The threat categories from 161 published crocodilian monitories articles for the three families of crocodilians. The threats mentioned in studies of the A) Alligatoridae, B) Crocodylidae and C) Gavialidae.

Census techniques

Use of monitoring methods increased steadily after 1970, with a marked rise after 2007 (Figure 3A). The highest number of publications occurred in 2020. Night-time spotlight counts were the dominant monitoring method (54% of studies), followed by diurnal counts (23%) and crewed aerial surveys (9%; Figure 3B). Mark–recapture accounted for 7%, UAV surveys 3%, and other techniques 5%.

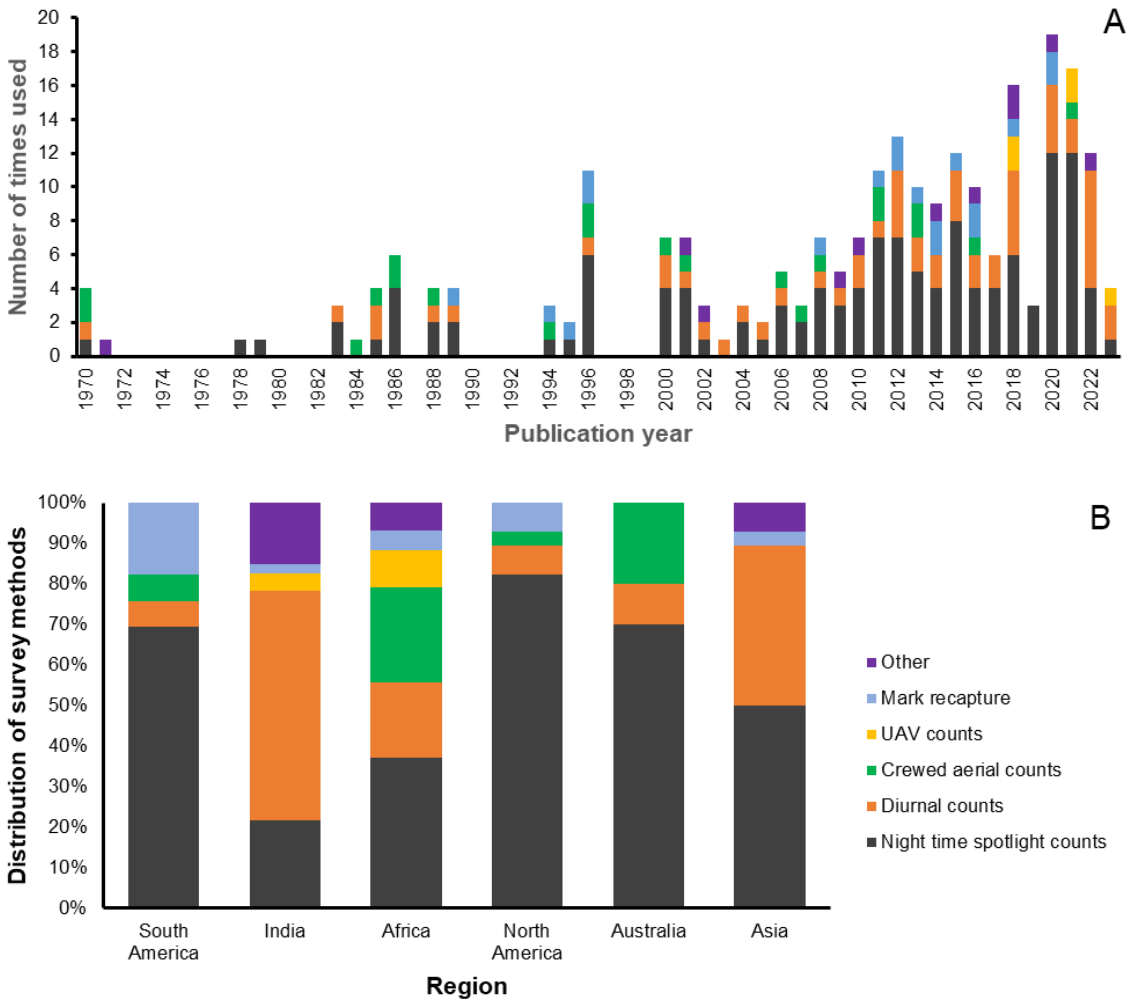


Figure 3. The different survey techniques used globally to monitor crocodilians. A) A time series showing the number of times a survey technique was used in published crocodilian population-monitoring studies between 1970 and 2023. B) The percentage of each survey technique used across six regions globally, based on 161 published studies.

Monitoring effort was spatially concentrated in specific regions, particularly northeastern parts of southern Africa, the Florida Everglades, northern Australia, and parts of India and Nepal (Figure 4).

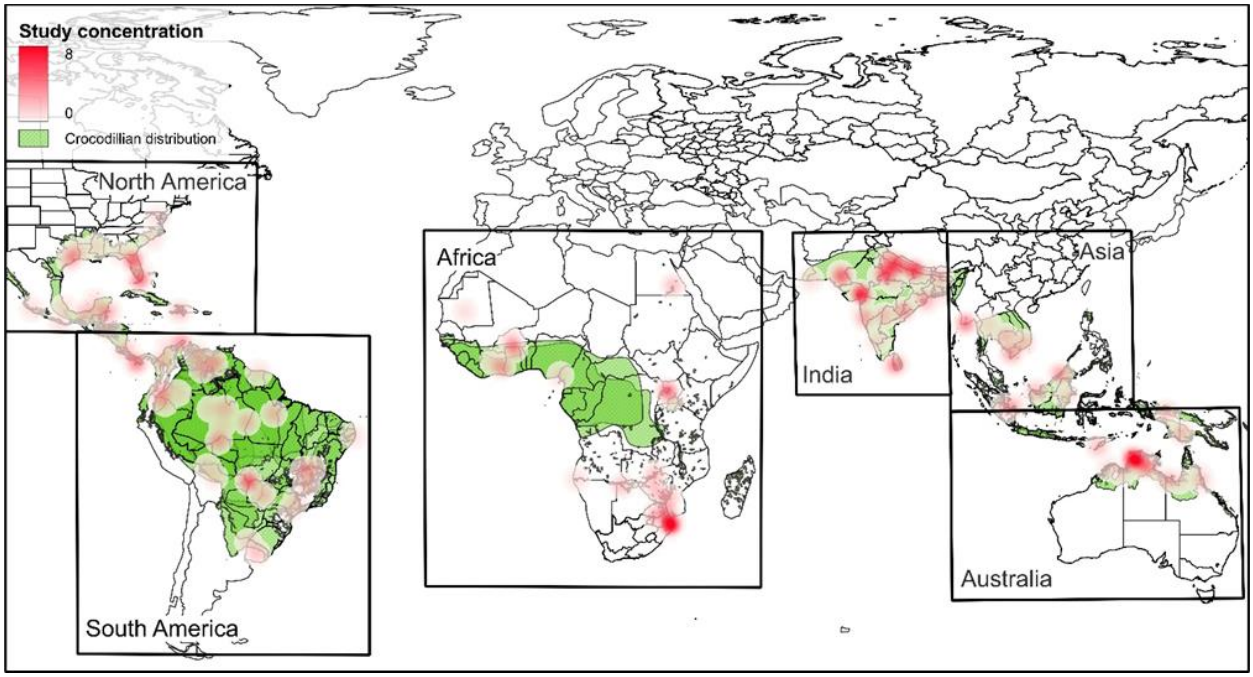


Figure 4.: Density heatmap illustrating the concentrations of published crocodilian population monitoring studies in six different regions of the world. The green areas illustrate the known distribution of crocodilians (IUCN, 2023). The six regions are designated by squares.

Reported limitation

Although 111 studies did not explicitly report limitations, when mentioned, the most common constraints were accessibility to the study area and area extent (Figure 5). Safety concerns were most frequently reported in Africa, India, Australia, and South America, while permitting limitations were more common in Asia (Figure 6).

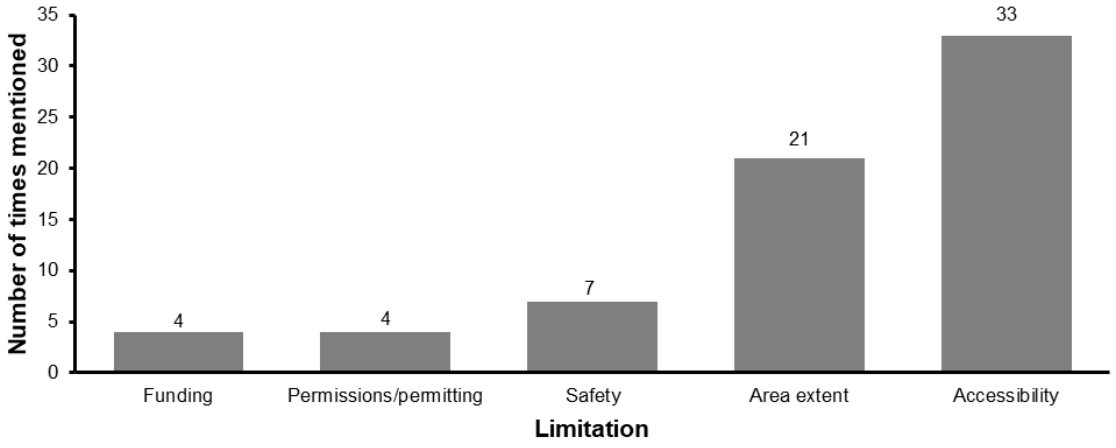


Figure 5. The number of times a limitation category was mentioned in a study.

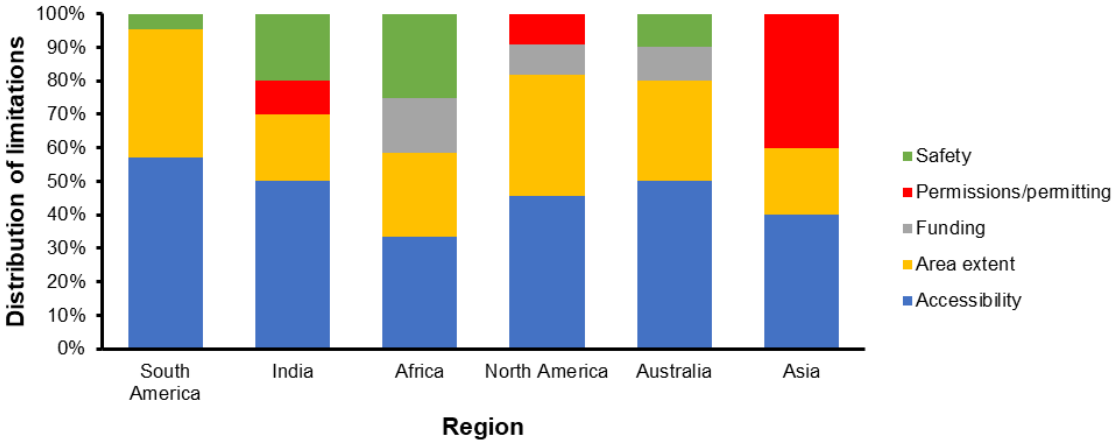


Figure 6. The percentage of limitation categories mentioned in studies from six regions worldwide.

Population trends and monitoring duration

Seventy studies did not conclude a population trend. Among those who did, the most reported trend was a decrease in population, followed by an increase (Figure 7).

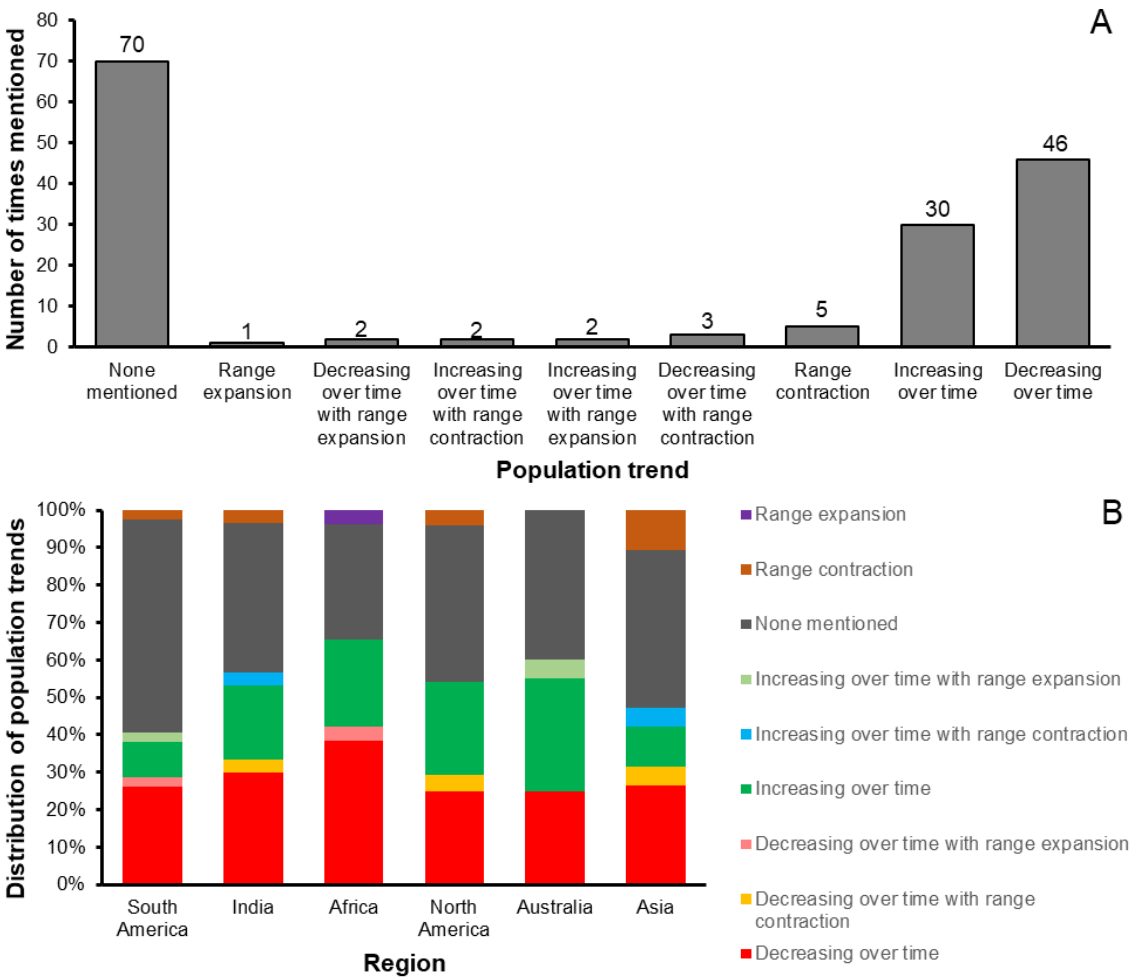


Figure 7. The crocodilian population trends mentioned in 161 published crocodilian population monitoring articles. The number of studies within each class of population trends (A). The percentage of studies of each trend class within six different regions worldwide (B).

Across crocodilian families, population decline was the most frequently reported trend for Alligatoridae, Crocodylidae, and Gavialidae (Figure 8).

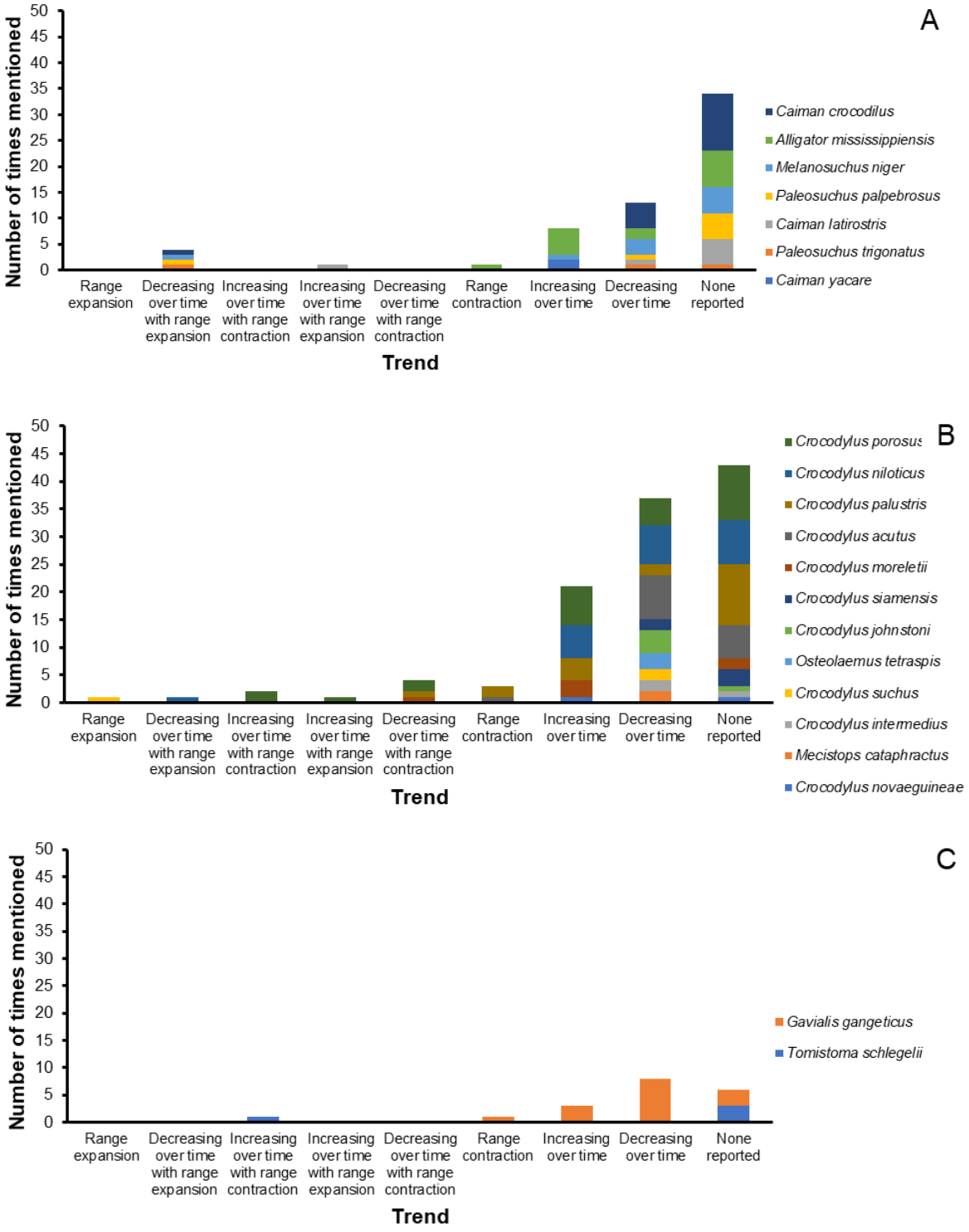


Figure 8. The population trend classes for the three families of crocodilians from 161 published articles on crocodilian population monitoring. The population trend from studies on A) Alligatoridae, B) Crocodylidae and C) Gavialidae.

Most monitoring studies were short-term (0–5 years; Figure 9A). Long-term monitoring (>10 years) were rare. Survey duration for individual surveys typically exceeded five days (Figure 9B), and most results were published within one year of fieldwork completion (Figure 9C).

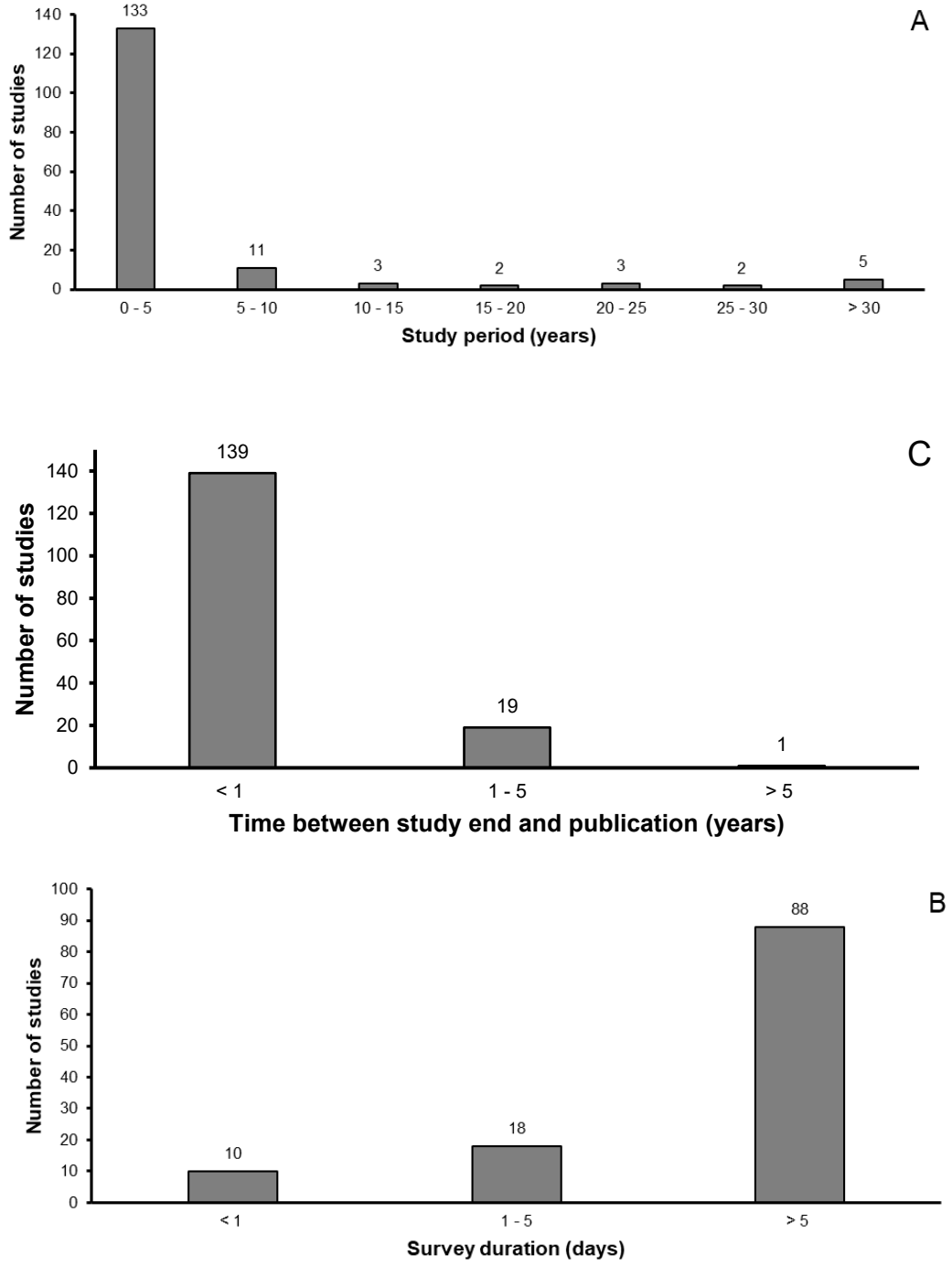


Figure 9. The temporal characteristics of 161 published crocodilian population monitoring studies. The period of the study conducting fieldwork given in years (A), the period of a single survey during the study given in days, and C: the time in years to publish the data after the completion of fieldwork (B).

Case study comparisons

Comparisons of census techniques in the Olifants River Gorge (Kruger National Park) and the Olifants River reach below Loskop Dam revealed clear differences in detection rates and survey effort among spotlight, crewed aerial, and UAV methods. Survey effort was standardised as total person-hours and person-hours per kilometre to enable direct comparison.

For the 12.3 km river section, spotlight surveys required 60 person-hours and recorded 419 crocodiles (Ferreira & Pienaar, 2011). The fixed-wing aerial survey required 12 person-hours and recorded 101 individuals (Myburgh, 2021). UAV surveys required 16 person-hours and recorded 450 crocodiles (Myburgh, 2021).

Spotlight counts had the highest labour requirement per kilometre. UAV surveys produced the highest total count with substantially lower effort than spotlight surveys. The fixed-wing survey required the least effort but recorded the fewest individuals (Figure 10).

Qualitative differences were also observed. The fixed-wing aerial survey was rapid and suitable for larger areas, but appeared to under-detect smaller individuals. Spotlight counts allowed closer inspection and size estimation of animals, but were labour-intensive and exposed surveyors to safety risks associated with nocturnal river surveys. UAV surveys generated high-resolution orthomosaic imagery, enabling repeated, independent counts within a GIS environment, improving repeatability and enabling post-survey verification of detections.

In the Olifants River reach below Loskop Dam, spotlight surveys required the highest effort per kilometre (Figure 11). Multiple observers independently counted individuals per section. Spotlight counts recorded a higher proportion of juveniles and yearlings, with an average of 2.7 crocodiles per section. UAV surveys required fewer person-hours per kilometre and produced orthomosaic imagery, allowing independent post-flight counts. Detection was dominated by adults, with few juvenile observations.

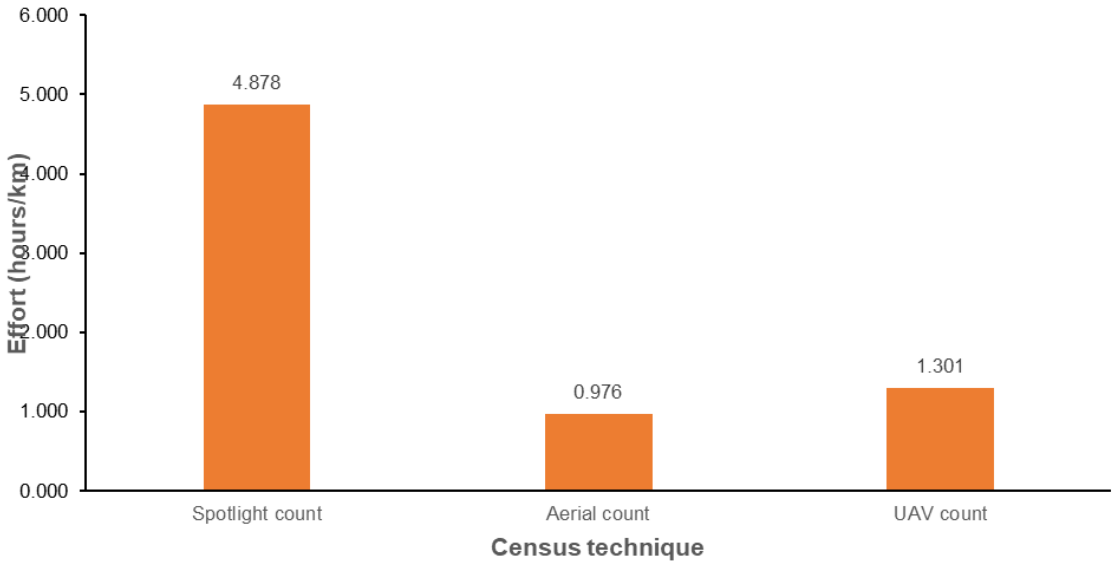


Figure3 10. The effort (hours/km) required to conduct a single survey is compared across three census techniques in the Olifants River Gorge of Kruger National Park.

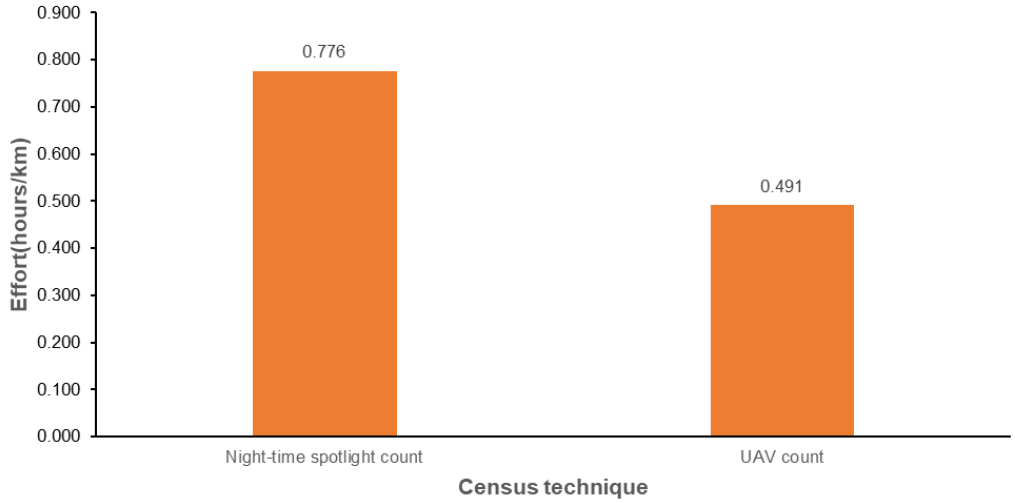


Figure 11. The effort (hours/km) required to conduct a single survey was compared between two census techniques in a reach of the Olifants River below Loskop Dam.

Across both systems, UAV surveys consistently required fewer person-hours per kilometre than spotlight surveys while producing comparable or higher adult counts. Spotlight surveys detected smaller size classes more frequently. Crewed aerial surveys required the least labour but recorded the lowest abundance.

Discussion

Global crocodilian populations are exposed to different anthropogenic pressures, particularly pollution and habitat degradation, hunting and poaching, and human-wildlife conflict (Somaweera et al., 2020). The consistency of these threats across regions and taxa suggests that long-term ecosystem-scale degradation drives many population declines. Many studies did not conclude clear population trends, reflecting limitations in monitoring duration, spatial coverage, and methodological consistency.

Night-time spotlight counts are widely used in crocodilian monitoring due to the technique's cost-effectiveness, but these surveys are labour-intensive, constrained by accessibility, and subject to safety risks and imperfect detection (Calverley & Downs, 2014; Combrink et al., 2011). Observer and visibility bias further reduce precision (Bayliss, 1987; Cartagena-Otalvaro et al., 2020), helping explain why repeated surveys often fail to establish reliable trends.

Crewed aerial surveys improve coverage of larger systems and reduce field risk, but under-detect smaller or partially submerged individuals, as demonstrated in the Olifants River Gorge case study and supported by previous findings (Lyet et al., 2016).

UAV surveys showed the highest detection efficiency relative to effort during the Kruger National Park case study. This technique required less effort and recorded the highest adult abundance. Permanent orthomosaic datasets are produced as references, and surveys are more repeatable. The Loskop Dam case study revealed reduced detection of juveniles, indicating size-related bias linked to image resolution and vegetation concealment. Thus, UAVs mitigate several logistical and safety constraints of traditional methods but do not eliminate detection bias.

Global crocodilian monitoring is dominated by short-term, geographically concentrated surveys, where most studies span fewer than five years and focus on well-known species such as *Crocodylus niloticus*, *C. porosus*, and *C. palustris*, while range-restricted and critically endangered species receive less attention. This uneven effort risks management decisions based on incomplete datasets.

Effective adaptive management efforts require precise, standardised, and long-term datasets (Lovett et al., 2007; McCarthy & Possingham, 2007). The Nile crocodile die-off in the Olifants River Gorge illustrates how inconsistent methods and limited baseline data complicate the interpretation of population change (Ashton, 2010; Ferreira & Pienaar, 2011). Illustrating that distinguishing real demographic shifts from survey artefact becomes difficult when methodologies vary.

No single census technique provides an unbiased representation of demographics. Spotlight surveys detect juveniles but are labour-intensive; aerial surveys maximise coverage but under-detect smaller individuals; UAV surveys improve efficiency, safety, and repeatability but may under-represent smaller size classes. An integrated framework combining UAV-based spatial coverage with targeted ground surveys offers the most balanced approach. Continued technological development, including automated detection from aerial imagery (Aubert et al., 2021; Woolcock et al., 2022), may further enhance monitoring, but standardised protocols remain essential to ensure comparability and long-term reliability.

Conclusion

Crocodilian populations face persistent anthropogenic threats, particularly pollution and habitat degradation, hunting and poaching, and human–wildlife conflict. Although monitoring efforts have increased, they remain geographically biased, short-term, and methodologically inconsistent, limiting the ability to establish reliable population trends for adaptive management.

The South African case studies show that each census method has strengths and weaknesses. Spotlight counts detect juveniles effectively but are labour-intensive and prone to bias; crewed aerial surveys provide rapid coverage but under-detect smaller individuals; and UAV surveys improve efficiency, safety, and repeatability, yet under-represent juveniles. No single method provides unbiased demographic representation.

Effective conservation requires integrated, standardised, and long-term monitoring frameworks that combine complementary techniques. Expanding systematic monitoring and adopting emerging technologies, particularly UAVs, will be essential to improve data accuracy and support informed management decisions.

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