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ORIGINAL RESEARCH

Low-cost uncrewed aerial vehicles (UAVs) as a novel tool for welfare assessments on open pen commercial crocodile farms

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Background: The welfare of crocodiles on commercial farms in southern Africa requires precise assessment, focusing on stocking densities and pen conditions. However, disputes between animal welfare groups and farm owners persist due to inadequate methodologies for quantifying these factors.

Objectives: This study aimed to address these disputes and enhance crocodile welfare assessment by introducing a novel technique using a low-cost consumer uncrewed aerial vehicle (UAV) and open-source photogrammetry software. The objective was to quantify key welfare parameters accurately and efficiently.

Method: The study involved applying the UAV-based technique to two large Nile crocodile (*Crocodylus niloticus*) farms in South Africa. The approach enabled the mapping and surveying of crocodile pens, facilitating the determination of stocking densities, biomass indicators, and other pen-related attributes. Comparisons were made between UAV-derived crocodile counts and farmer estimates.

Results: The UAV-based crocodile counts significantly differed from the estimates provided by farmers, underscoring the need for a more precise assessment method. The technique's cost-effectiveness was evident, with implementation expenses totalling less than R10 000, a fraction of the cost associated with commercial UAV surveys.

Conclusions: The introduced UAV-based technique offers a valuable solution to the ongoing debates regarding crocodile welfare on commercial farms. By quantifying key parameters accurately and economically, it empowers farmers and animal welfare groups to make informed decisions. The method's ease of adoption, demonstrated through its use by some Southern African crocodile farmers, signifies its potential for widespread application, ultimately contributing to improved crocodile welfare.

Keywords: animal welfare, commercial, stocking densities, uncrewed aerial vehicle, photogrammetry

Introduction

Crocodilians, as amphibious, ectothermic reptiles, rely on heterogeneous environments for their survival, growth, and reproduction, with these requirements being particularly important in commercial farms (Huchzermeyer 2003; Bothma & Van Rooyen 2005; Downs et al. 2008). In general, specialists working on commercial crocodile farms usually focus on animal health and production as indicators of good animal welfare (Mellor et al. 2020). Optimal animal welfare also includes consideration of the animal's affective state (i.e. how the animal feels or sentience), as well as an emphasis on natural living (i.e. consideration of whether the animal can express natural behaviours) (Mellor et al. 2020).

Elevated stocking densities have been linked to heightened stress and increased antagonistic interactions among captive animals, resulting in compromised health (Elsey et al. 1990; Davis 2001; Bothma & Van Rooyen 2005; Brien et al. 2008, Brien 2015; Veldsman 2019; Webb et al. 2021). This adversely affects growth rates, resource investment per unit product, and product quality (products from crocodile farms are typically crocodile leather [or skins for processing to leather products] and crocodile meat) (Shilton et al. 2014; Webb et al. 2021). Improved welfare not only enhances profitability by increasing yields and minimising resource consumption, but also aligns with the demands of crocodilian product buyers for certified, well-managed farms (Manolis & Webb 2016).

Despite the significance of adequate space allocation (Spoolder et al. 2000; Thomas et al. 2004; North et al. 2006; Weeks et al. 2008), there is a lack of evidence-based welfare parameters for commercial crocodile farms (Elsey et al. 1990; Davis 2001; Poletta et al. 2008; Ganswindt et al. 2014; Webb et al. 2021). Precise measurement of stocking densities and related pen parameters (e.g. waterbody size) is often lacking or completely absent. In light of the disparities in recommended stocking densities (Veldsman 2019; Webb et al. 2021), adherence to general guidelines (SANS 2009; CFAZ 2012) is crucial but insufficient, and the need for a holistic approach to welfare evaluation is evident (G.E. Swan unpublished data 2021; Mellor et al. 2020).

The stocking density of crocodiles per pen on a commercial farm is sometimes unknown, paralleled by imprecise measurements of total pen size (m^2) and associated parameters (e.g. waterbody size, waterline length). In cases where specific recording systems are absent, there is potential for misrepresentation of the number of animals per pen, particularly in breeder pens. It is also important to specify individual crocodile sizes, particularly when considering animal density (Webb et al. 2021). The measurement of individual crocodile size is feasible for smaller animals (< 1 m total length [TL]). For larger Nile crocodiles (*Crocodylus niloticus*), stocking density and other welfare parameters are predominantly estimations, and physically measuring the sizes of numerous breeder animals is impractical (Carpenter et al. 2021).

In southern Africa, communal and single pen systems are used on Nile crocodile commercial farms, usually with one waterbody for each pen; and these waterbodies generally have different designs, shapes, sizes and water depths (Carpenter et al. 2021). Whilst pen design determines the available area per animal (total pen m^2/number of animals in the pen), waterbody design is multifaceted. It includes considerations of waterline length (the length of beach line or water's edge and the zone of interaction between crocodiles), water surface area to water-line ratios and the distance to the water from any point within the pen. The waterline is considered extremely important from a management and welfare perspective; shorter waterlines (high number of animals per meter of waterline) have more intense movement of animals in and out of the water per specific length (m). This interaction between animals crossing the waterline may lead to more interaction between animals and damage to skins (Veldsman 2019). In South Africa, most commercial farms use one waterbody (usually square or rectangular) per pen for growers (Carpenter et al. 2021). In the case of adult breeders, the water-line is usually much longer because of the more natural shapes (bays and undulating waterlines) of some of the waterbodies in their enclosures (Carpenter et al. 2021). On commercial crocodile farms, it is possible to have optimal crocodile stocking densities (number of crocodiles per total pen m^2) with inadequate water area or waterlines if waterbodies are too far apart (in case of multiple waterbodies per pen), or too small, potentially hindering the crocodiles' thermoregulatory capabilities (Webb et al. 2021).

A review of the literature evaluating proposed crocodilian stocking densities exists, but there is generally a lack of consistency between proposed stocking densities for various crocodilian species (Veldsman 2019; Webb et al. 2021). In South Africa and Zimbabwe, crocodile farms presently rely on regulations set out by the South African Bureau of Standards (SANS 2009) and the Crocodile Farmers Association of Zimbabwe (CFAZ): Codes of Practice (CFAZ 2012), which are general guidelines based on *The Code of Practice on the Humane Treatment of Wild and Farmed Australian Crocodiles* (NRMMC 2009). These guidelines are based on historical research and acknowledge the need for improved methods of determining and evaluating stocking densities and other welfare parameters on commercial crocodile farms (Manolis & Webb 2016). Although generalised numerical values serving as guidelines for stocking densities of Nile crocodiles on commercial farms are still important, a more holistic approach for the evaluation of farm crocodile welfare and "well-being" is becoming more relevant (G.E. Swan unpublished data 2021; Mellor et al. 2020).

The use of UAVs or drones for mapping and monitoring has been limited to larger commercial operations with access to proprietary software packages and high-cost commercial uncrewed aerial vehicles (UAVs). Recently, consumer-grade UAVs have been applied to various ecological studies and are capable of producing georeferenced and geometrically corrected orthophotographs of relatively large areas when combined with photogrammetry software packages (Anderson et al. 2013; Hodgson et al. 2016; Ezat et al. 2018; Buters et al. 2019; Scarpa & Pina 2019; Fritsch & Downs 2020; Myburgh et al. 2021). Consumer-grade UAVs and open-source software with comparable accuracy to proprietary commercial alternatives present a novel approach to mapping and monitoring of smaller areas and are well suited for smaller crocodile farming operations with lower budgets.

In the present study, we assessed the applicability of low-cost UAV surveying as a tool for welfare evaluation on two commercial crocodile farms in South Africa. We evaluated the potential of using a low-cost consumer-grade UAV and open-source software packages to determine crocodile stocking densities and several other environmental parameters in open-air grower communal pens and breeder holding facilities. We predicted that the UAV counts would be higher than the farmer estimates of the number of Nile crocodiles per pen and that the stocking densities would be misrepresented, especially in grower pens where stocking densities are relatively difficult to estimate because of the smaller size (usually 0.5 to 1.8 m [TL]) of the animals. We further assumed that more naturally shaped ponds and those with islands would provide longer waterline lengths.

Research methods and design

This research was approved under the University of KwaZulu-Natal, School of life Sciences ethics committee number 020/15/Animal.

UAV flights

We conducted three flights over two non-consecutive days at two commercial Nile crocodile farms. All flights were conducted on early winter mornings between 10h00 and 11h00 as per Calverley and Downs (2014). All flights were conducted using a DJI Mavic Mini (Da Jiang Innovations, Shenzhen, China) (available for ± R5 500/US$399 from most South African suppliers e.g. Takealot) flown with Dronelink flight planning software (available for US$49,99 from Dronelink [Dronelink, Austin, Texas]) installed on a smartphone connected to the DJI Smart controller. All flights were pre-programmed through the Dronelink web interface and were constrained to the flight variables listed in Myburgh et al. (2021). Flight altitude was constant for all flights at 40 m relative to the take-off location. During flights, the UAV took a series of photographs with specified overlap that were used to construct orthophotograph mosaics of the areas of interest. Farm A was small enough to be covered entirely by one flight lasting approximately 12 min, and farm B required two flights of five and nine min, respectively. Combined, we surveyed a total of 10.5 ha and took 455 photographs.

Image processing

We processed all images with OpenDroneMap (ODM) through the WebODM interface on a notebook computer running an AMD® Ryzen™ 7 3700U quad core processor with a maximum

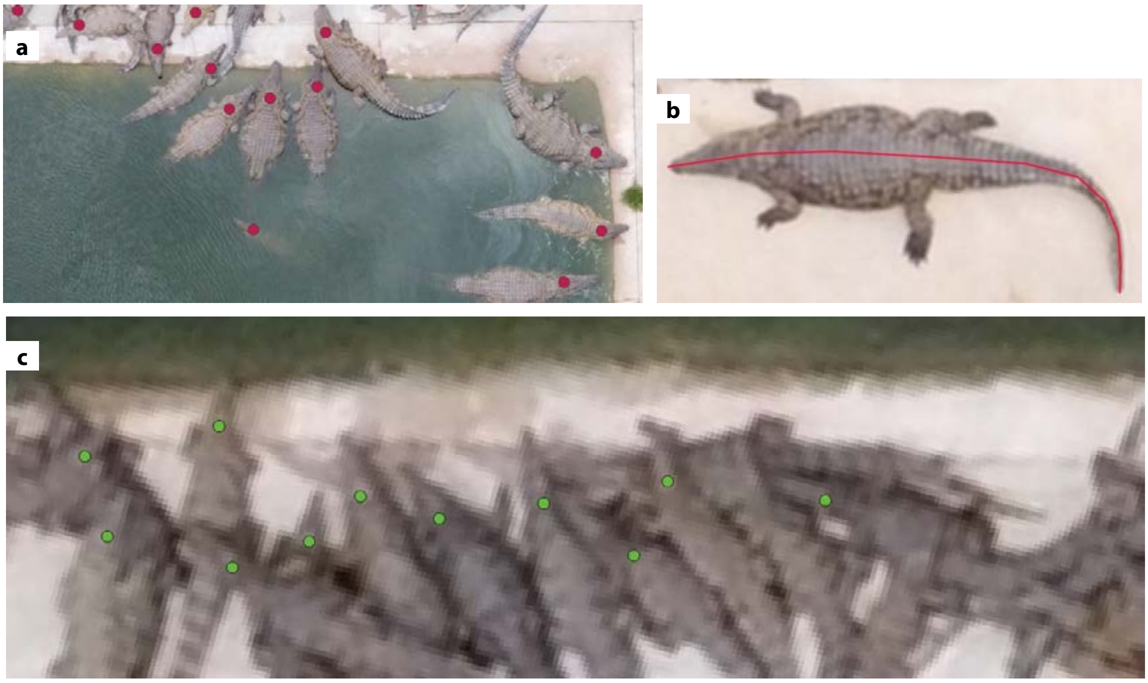

Figure 1: An illustration of (a) how breeder and (c) grower Nile crocodiles in orthophotographs were counted, and (b) measured using point and line layers in QGIS. Breeder crocodiles are approx. 3 m in length and growers approx. 1.5 m. Note the difficulty in identifying the head of a grower crocodile in Figure 1c.

clock speed of 2.3 GHz with 20 GB of DDR4 RAM and an Intel® solid-state drive (SSD). Orthophotograph resolution was constrained to the GSD (ground sampling distance; in cm/pixel) of the original images at 1.42 cm/pixel. We converted processed orthophotographs as georeferenced Tag Image File Format (.tif) files and imported these into QGIS (QGIS Development Team [2021]). These methods have been shown to produce orthophotographs with measurement errors of < 50 mm without ground control points and are adequate for deriving accurate estimates of crocodile farm variables (Myburgh et al. 2021).

Determination of crocodile and pen related variables

We counted Nile crocodiles by creating a vector (Point) layer in QGIS where a point could be placed on each crocodile head that was visible in orthophotographs (Figure 1a) and obtained data on the number of Nile crocodiles per pen as documented by the respective farming operations. Nile crocodile lengths were determined by creating a vector (LineString/CompoundCurve) layer, from the first pixel representing the crocodile's snout following the curve of its back to the last pixel representing the tip of the crocodile's tail, and extracting the geometry attributes thereof (Figure 1b). Crocodile sizes were then divided into size classes of 10 cm increments to investigate size class distributions within pens. Breeder pens were relatively easy to count when compared with grower pens, where crocodiles were much smaller and often clumped, making the identification of individuals difficult (Figure 1c).

We created geo-package (polygon/multi polygon) layers for all Nile crocodile pens and ponds observed in the orthophotographs and derived their geometry attributes in QGIS. We omit illustrations of the pen and pond designs to preserve farm anonymity. Crocodile holding pens are divided into breeder (B) and grower (G) pens for both farms A and B (e.g. breeder and grower pens on farm A were designated AB and AG, respectively). We used the Nile crocodile count to infer stocking density, expressed as a function of various other parameters (animals per unit area), while we used crocodile length as an indicator of biomass (length in m per unit area or length).

For all open-air pens and ponds, we were able to derive the area and circumference, enabling estimations of waterline length and total water area, as well as the percentage water area in the respective pens (Table II). Stocking densities could then be determined as the number of animals per unit area (pen/pond). We expressed water efficiency per pen as the total water area (m^2) as a function of waterline length (m) in each pen. We expressed water availability per pen as the total percentage of pen area covered by water in each pen.

Statistical analyses

We used a t-test to compare farmer estimates with UAV-derived Nile crocodile counts, and used a linear regression to evaluate the relationship between the number of crocodiles per unit area and meters of crocodile per unit area. We used a Shapiro-Wilk test for size class estimates to compare crocodile size distributions in pens with high and low stocking densities.

Results

We counted a total of 7 147 Nile crocodiles in 16 pens on the two commercial crocodile farms (Farms A and B) and we determined TLs for a total of 1 887 Nile crocodiles.

For all open-air pens and ponds, the area and circumference could be derived, enabling estimations of waterline length and total water area, as well as percentage water area in pens (Table I). Water efficiency (m/m^2) was expressed as total water area (m^2) as a function of waterline length (m) and water availability was expressed as the total percentage of pen area covered by water. Note that only pen BB2 has a water area > 50%. Pen BG4 had the greatest water efficiency with 1.42 m of waterline per m² of water and the highest biomass load at 3.84 m of crocodile/m² of water. The ponds in this pen were merely three furrows, approximately 1.5 m across, whilst the average crocodile length in this pen was 1.2 m. Pen BB2 had the lowest water efficiency at 0.14 m of waterline per m² of water, and the pond in this pen covered approximately 60% of the total pen area with 0.17 m of crocodile/m² of water. The crocodiles in this pen were notably more clumped, with few animals in the middle of the pond.

For some Nile crocodile breeder pens housing older animals, significant size discrepancies distinguished between males and females (Figure 2). We used length

Figure 2: A cohort of crocodiles in an established breeder pen with significant size discrepancy allowing the differentiation of sexes.

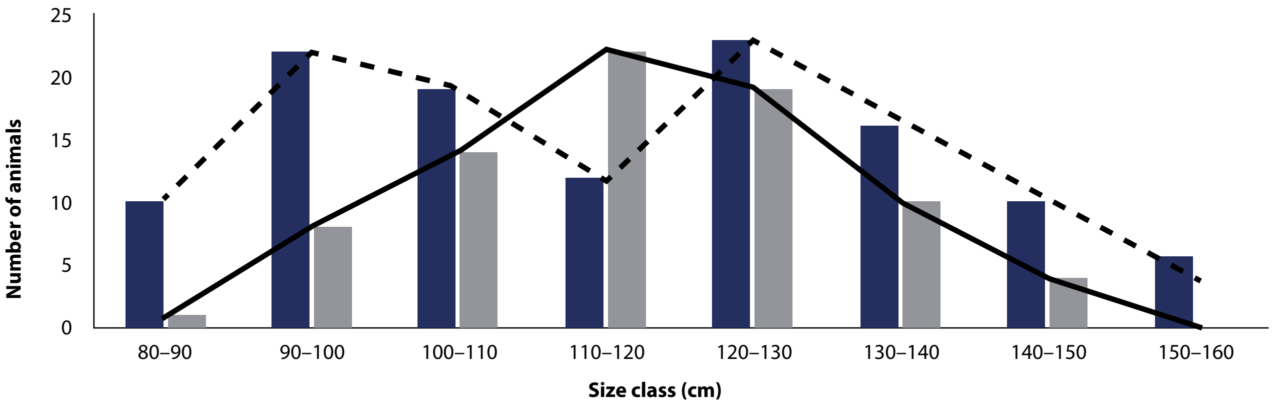

Figure 3: An example of two size distribution curves derived from length measurements of Nile crocodiles from two separate grower pens where the grey bars and solid line represent pen BG3 with a stocking density of 0.17 animals/m² and the blue bars and dashed line represent pen AG9 with a stocking density of 0.83 animals/m².

Table I: Pen and pond characteristics derived from drone images combined with photogrammetry and GIS software for 16 pens across two commercial crocodile farms (A and B) hosting both breeder (xB#) and grower (xG#) stock (See definitions in text).

Pen variables			Pond variables			
Pen code	**Pen area**	**Pen circumference**	**Water area (m²)**	**Waterline (WL)(m)**	**Water efficiency (m/m²)**	**Water availability (% of total pen area)**
AB1	5446	317	1139	284	0.25	20.91
AB2	8490	390	3003	492	0.16	35.37
AG1	1420	149	486	91	0.19	34.23
AG2	607	115	252	88	0.35	41.52
AG3	426	82	186	74	0.40	43.66
AG4	643	99	285	98	0.34	44.32
AG5	767	108	321	102	0.32	41.85
AG6	1031	129	359	101	0.28	34.82
AG7	932	122	356	103	0.29	38.20
AG8	842	124	291	92	0.32	34.56
AG9	504	90	205	78	0.38	40.67
BB1	12565	513	4018	850	0.21	31.98
BB2	4835	299	2760	393	0.14	57.08
BG1	6908	335	3411	543	0.16	49.38
BG3	2843	214	531	222	0.42	18.68
BG4	134	46	50	70	1.40	37.31

Table II: Welfare parameters for 16 pens across two commercial crocodile farms (A and B) hosting both breeder (xB#) and grower (xG#) stock derived from UAV imagery combined with photogrammetry and GIS software

Pen code	Crocodile count and lengths				Density and biomass indicators				
	Farm estimate	UAV-derived count	Length measured (*n*)	Mean length (cm)	Absolute density (animals/m²)	Waterline density (animals /mWL)	Absolute biomass (m of crocodile /m²)	Waterline biomass (m of crocodile/ mWL)	Water-specific biomass (m of crocodile/m² of water)
AB1	800	226	141	319	0.04	0.80	0.13	2.54	0.63
AB2	2000	398	268	307	0.05	0.81	0.14	2.48	0.41
AG1	3400	930	124	139	0.65	10.22	0.91	14.21	2.66
AG2	965	710	164	102	1.17	8.07	1.19	8.23	2.87
AG3	396	420	110	124	0.99	5.68	1.22	7.04	2.80
AG4	950	669	146	116	1.04	6.83	1.21	7.92	2.72
AG5	788	515	112	134	0.67	5.05	0.90	6.77	2.15
AG6	676	456	115	130	0.44	4.51	0.57	5.87	1.65
AG7	674	540	121	138	0.58	5.24	0.80	7.23	2.09
AG8	787	674	144	118	0.80	7.33	0.94	8.64	2.73
AG9	386	417	122	113	0.83	5.35	0.93	6.04	2.30
BB1	431	239	84	293	0.02	0.28	0.06	0.82	0.17
BB2	316	161	61	297	0.03	0.41	0.10	1.22	0.17
BG1	254	158	49	200	0.02	0.29	0.05	0.58	0.09
BG3	1000	474	78	78	0.17	2.14	0.13	1.67	0.70
BG4	400	160	48	120	1.19	2.29	1.43	2.74	3.84

estimates to derive size distributions (Figure 3) and split these into size classes (designated every 10 cm; e.g. 100–110 cm; 111–120cm, etc.) to compare size distributions across pens. For example, in pen AG9, size classes were bivariate and non-normally distributed (Shapiro-Wilk test; $p = 0.01329$), and in pen BG3 with a lower stocking density, size classes were normally distributed (Shapiro-Wilk test; $p = 0.6467$).

The number of Nile crocodiles per pen counted from orthophotographs differed significantly from farmer estimates ($n = 15$, $p < 0.05$). When compared with farm owners estimates of Nile crocodile stocking densities, orthophotograph counts were almost exclusively lower, with the exception of pen AG9. In some cases, like pen AB2, the farmer estimated 2 000 animals whilst counts from orthophotos were much lower at 398. Nile crocodile pen and pond characteristics were combined with crocodile counts and length measurements to derive several indicators of crocodile welfare (Table II).

Discussion

This study presents novel insights into Nile crocodile welfare parameters on commercial farms through the utilisation of a low-cost UAV and open-source photogrammetry software. Total counts derived from orthophotographs revealed potential underestimations of actual stocking densities, yet the method ensured a realistic upper limit for crocodile counts per pen. Although more robust than simply estimating numbers, the technique has a number of shortfalls that can be addressed in subsequent research. The technique could miss submerged animals in circumstances where water clarity prevents their detection. This is a more pronounced issue in breeder pens where the water bodies are often larger and deeper than those in grower pens and multiple counts over the course of a day could address this shortcoming (Viljoen et al. 2023).

A noteworthy discrepancy emerged between farmer estimates of Nile crocodile stocking densities and orthophotograph-based counts. This novel approach challenges welfare organisations to adopt more objective methods, like UAV technology, for holistic evaluations of specific pen or farm welfare parameters.

Whilst smaller crocodilians (< 1 m TL) are often transferred between pens and can be counted with relative ease during handling, in bigger pens with larger animals (> 1 m TL), estimates of stocking densities are typically obtained by tracking deaths and additions to cohorts across multiple pens (Carpenter et al. 2021). Our findings unveil the limitations in relying on farmer estimates, as the obtained orthophotograph counts were notably lower. This discrepancy is particularly pronounced in grower pens, where smaller and more densely stocked crocodiles contribute to a challenging estimation process. In contrast, the technique more effectively gauges larger breeder pens, which also emerged as the most sizeable enclosures on the farms and farmers acknowledged that their estimates of stocking densities were most likely inaccurate, owing to the difficulty of counting animals in such large enclosures (Carpenter et al. 2021). However, overestimation of actual stocking densities in all but one pen bodes well for the welfare of animals on commercial crocodile farms.

When minimum and maximum stocking densities derived from drone imagery were compared with stocking densities recommended by the South African National Standards document (SANS 2009) and CFAZ (2012), the results showed that drone-derived densities for grower crocodiles fell within the recommended guideline ranges. In contrast, we found breeder crocodile densities did not fit the recommended norms, and our data showed that these pens were overstocked.

Pen and pond size are two significant factors to consider when assessing stocking densities in commercial crocodile farming since both land and water areas are important for thermoregulatory and breeding activities (SANS 2009; CFAZ 2012; Manolis & Webb 2016). Water area per animal is as important as land area per animal as crocodiles are ectotherms that thermoregulate behaviourally with basking, shuttling and posturing (Downs et al. 2008). With insufficient space per crocodile in a captive pen, not all animals can successfully regulate their body temperatures if access to water and land are limited (Seebacher 1999; Downs et al. 2008; Manolis & Webb 2016).

Breeding behaviours of crocodiles are also space-reliant, which means that sufficient space for breeding-territory formation and the act of mating in water bodies is necessary (SANS 2009; CFAZ 2012). Industry recommendations are that water bodies cover approximately 50–70% of the area of the pens and that all crocodiles in a captive pen should be able to submerge (Bothma & Van Rooyen 2005; Brien et al. 2008; Shilton et al. 2014). In the present study, we found only one pen (pen BB2) had a percentage water area above 50%, with some ponds covering as little as 18% of the total available area in the pens. Pond area could be increased by decreasing the total pen area; however, such an approach would negatively affect stocking densities.

Absolute density and absolute biomass indicate current space allowances per crocodile, enabling stocking density adjustments. Waterline density could be a useful indicator of basking space per animal; ideally, all crocodiles should be able to bask near or on the waterline. Water-specific biomass could show whether a pond is adequate in size per the number of crocodiles in the captive pen. For this last parameter, pond depths could be included, and water body volume can be considered. WebODM (the open-source photogrammetry software package interface) has a built-in tool for volumetric calculations (Toffanin 2019). Ponds are routinely drained and cleaned, so this could easily be achieved by conducting flights over pens whilst ponds are empty.

The ability to estimate crocodile sizes remotely provides a means of evaluating size class distributions within pens (size variance in same-age groups result from runting or failure to thrive syndrome (FTTS) (Brien et al. 2008). Overstocking introduces more chances for competition and results in preferential resource utilisation where larger animals (bullies) obtain more food, exacerbating the size variance within a pen (Veldsman 2019). This can be difficult to manage once it has occurred as larger operations have pens with many hundreds of animals, making it difficult to identify and remove smaller individuals. Once the effects of overstocking have occurred, it often remains within the cohort until slaughter (Brien et al. 2008). Runting and FTTS will result in bivariate (not normally distributed) size distributions within a pen. Therefore, the present technique provides a novel aspect to crocodile farm management through remote size estimation and may be used in future studies to more accurately estimate the relationship between animal welfare and stocking density. We found that measurements of both crocodile numbers and average length could be used to estimate biomass within a pen. Indices of biomass can potentially be used to inform feeding and medication regimens.

Crocodiles in pen BG3 were absent from large parts of the pen that were not close to the water's edge. Therefore, if crocodiles on commercial farms do not use some areas that are too far away from a water body, numerical stocking density values can falsely be reduced by making the pen (land area) larger without increasing the available water area or waterline length. In essence, when farmers make pens bigger (land portion) to reduce the stocking density, it does not contribute welfare value because crocodiles often do not use areas far from the water. This gives a "false" low stocking density (on paper), but the stocking density in the pen is still high relative to the amount of water available. UAVs can be a valuable tool in determining the relationship between water and land availability, and future studies may consider using multiple flights to produce specific maps of space-use within pens to evaluate minimum and maximum water to land ratios within pens.

Conclusions

The introduced UAV-based methodology not only addresses current gaps in welfare assessment but also demonstrates the potential to inform future practices, policies, and research. The discordance between estimated and actual stocking densities highlights the need for more accurate methods, especially in larger and densely populated enclosures. The technique's ability to remotely estimate crocodile sizes suggests its potential application in evaluating size variance and its related consequences, such as competition and resource utilisation. Moreover, future research could delve into mapping space utilisation within pens, contributing to the determination of optimal water-to-land ratios. This study underscores the feasibility of UAV technology in advancing welfare assessment practices on commercial crocodile farms. The total cost of implementation is less than ZAR10 000/US$500, which is about 20% of the cost of a single day of UAV surveying by a commercial UAV operator in South Africa.

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Conflict of interest

The authors declare no conflict of interest.

Ethical approval

This research was approved under the University of KwaZulu-Natal, School of Life Sciences ethics committee number 020/15/Animal.

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