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QUANTIFYING THE SEVERITY OF GIRAFFE SKIN DISEASE VIA PHOTOGRAMMETRY ANALYSIS OF CAMERA TRAP DATA

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ABSTRACT: Developing techniques to quantify the spread and severity of diseases afflicting wildlife populations is important for disease ecology, animal ecology, and conservation. Giraffes (*Giraffa camelopardalis*) are in the midst of a dramatic decline, but it is not known whether disease is playing an important role in the broad-scale population reductions. A skin disorder referred to as giraffe skin disease (GSD) was recorded in 1995 in one giraffe population in Uganda. Since then, GSD has been detected in 13 populations in seven African countries, but good descriptions of the severity of this disease are not available. We photogrammetrically analyzed camera trap images from both Ruaha and Serengeti National parks in Tanzania to quantify GSD severity. Giraffe skin disease afflicts the limbs of giraffes in Tanzania, and we quantified severity by measuring the vertical length of the GSD lesion in relation to the total leg length. Applying the Jenks natural breaks algorithm to the lesion proportions that we derived, we classified individual giraffes into disease categories (none, mild, moderate, and severe). Scaling up to the population level, we predicted the proportion of the Ruaha and Serengeti giraffe populations with mild, moderate, and severe GSD. This study serves to demonstrate that camera traps presented an informative platform for examinations of skin disease ecology.

Key words: Camera traps, giraffe skin disease, lesions, photogrammetry, Ruaha, Serengeti, Tanzania.

INTRODUCTION

Emerging skin diseases have jeopardized populations of numerous species of conservation concern over the last quarter century. A facial tumor disease has reduced Tasmanian devil (*Sarcophilus harrisii*) populations by as much as 90% and threatens the extirpation of this species across its range (Jones et al. 2007; McCallum et al. 2007, 2009). White nose syndrome, characterized by fungal growth on the face and wings of afflicted bats (Phyllostomidae family), is associated with dramatic declines of scores of different bat species throughout North America (Blehert et al. 2009; Frick et al. 2010). Chytridiomycosis is a fungal disease affecting amphibian populations and causes large patches of skin to thicken and slough away, limiting an afflicted animal's ability to regulate osmotically (Voyles et al. 2009). This disease has devastated amphibian populations around the world in what has been called the biggest loss of biodiversity in recent history (Skerratt et al. 2007). Given the evident conservation implications of diseases that present externally (i.e., on the skin), there is a need to develop noninvasive, rapidly deployable, and highly scalable techniques that can quantify the prevalence and severity of skin diseases in wildlife populations.

Recent advances in photographic equipment and photogrammetry have expanded the focus of wildlife conservation research. Photogrammetry, the quantification of photographic images, has been used to measure morphological characteristics of rare and elusive species (Rothman et al. 2008; Willisch et al. 2013), estimate body size and mass of species of conservation importance (Waite et al. 2007; Berger 2012; Meise et al. 2014), and identify individual animals (via interpretation of unique markings) in a population (Bolger et al. 2012; Durban et al. 2015; Zheng et al. 2016). However, this potentially broad photogrammetry toolbox has been rather narrowly applied to questions relating to animal ontogeny, morphology, trait measurement, and the corresponding evolutionary implications of these factors (Berger 2012). The specific scope of this research largely derives from the difficulty of making precise calculations from images that lack a standardized reference scale (de Bruyn et al. 2009). The use of camera traps for studies of wildlife ecology has grown steadily over the last 10 years (Rowcliffe et al. 2008; O'Brien and Kinnaird 2011; Swanson et al. 2015) and holds great promise for assessing disease ecology given the ability to quantify animal occurrence and population density for a variety of species in a noninvasive way. However, given that animal subjects captured on camera traps lack a reference scale, photogrammetry of images deriving from this technological platform are rare (Hiby et al. 2009). Here we explored the productive use of camera traps to measure the severity of wildlife diseases that present on the derma of animal subjects.

Giraffe (*Giraffa camelopardalis*) populations have declined by approximately 40% over the past 30 yr with an estimated 100,000 remaining individuals in the wild (Muller et al. 2016). Currently nine giraffe subspecies are distributed across 21 countries in sub-Saharan Africa, and efforts are ongoing to update the conservation status of all giraffe subspecies. However, recently the status of giraffes as a species was changed from Least Concern to Vulnerable on the International Union for the Conservation of Nature's Red List (Muller et al. 2016). Giraffe population declines are largely attributed to habitat loss, poaching, human encroachment, and limited conservation attention (Giraffe Conservation Foundation 2013). However, emerging diseases, such as giraffe skin disease (GSD), may also be playing an important role in the conservation of giraffes (Epaphras et al. 2012; Muneza et al. 2016).

First detected in a single giraffe population in Uganda in 1995, GSD has now been recorded in 13 giraffe populations across seven African countries where it affects Masai (*Giraffa camelopardalis tippelskirchi*), Rothschild's (*Giraffa camelopardalis rothschildi*), Angolan (*Giraffa camelopardalis angolensis*), and South African (*Giraffa camelopardalis giraffa*) giraffes (Muneza et al. 2016). Although GSD exhibits anatomical variation in its manifestation across its distribution, the progression of the disease appears relatively consistent among these different populations. Giraffe skin disease first presents as small nodules on the skin where the hair becomes raised. These nodules develop into scabs that harden and develop into dry, scaly patches. As the disease progresses, the skin becomes itchy and then wrinkles to form large, grayish, alopecic lesions (Epaphras et al. 2012). In very bad cases, cracks form in these lesions, resulting in raw fissures that form pus and ooze.

Given the emergent nature of GSD, the factors that cause the disease and how it spreads are as yet unknown. Initial investigations suggest that filarial worms may be involved in the transmission of GSD, though no formal confirmation of etiology or pathogenesis of the disease has been carried out (Karimuribo et al. 2011; Epaphras et al. 2014). It is currently unclear whether GSD directly decreases survival or reproduction of affected individuals, but it is very possible that it makes affected animals more vulnerable to predation. Lions (*Panthera leo*) prey on adult and subadult giraffes (Hayward and Kerley 2005), while leopards (*Panthera pardus*) and hyenas (*Crocuta crocuta*) can kill calves (Hayward et al. 2006; Hayward and Kerley 2008). Giraffes are typically very adept at fending off predator attacks by running and kicking (Carter et al. 2013), but individuals with severe GSD appear to move with difficulty, which could make them more susceptible to lions (Epaphras et al. 2012). The disease is very widespread in Tanzania and has been documented in Ruaha National Park, Serengeti National Park, Manyara Ranch Conservancy, Tarangire National Park, and Selous Game Reserve (Karimuribo et al. 2011; Muneza et al. 2016; Fig. 1). Ruaha National Park has the highest recorded prevalence of GSD in Africa with 86% of the population afflicted (Epaphras et al. 2012, 2014; Muneza et al. 2017). However, and very importantly, this statistic documents the occurrence (presence or absence) of GSD, rather than its severity.

Only two studies have attempted to describe the severity of GSD. Kalema (1996) suggested that mild GSD involved small skin nodules measuring 2–3 cm with raised hair, moderate GSD was characterized by round or oval patches of lesions measuring 10–16 cm, and severe GSD was associated with raw fissures measuring >16 cm. The most recent study, carried out in northern Tanzania, proposed GSD lesions with a diameter between 1 and 30 cm as mild GSD, 31–60 cm as moderate GSD, and >60 cm or cracked skin as severe GSD (Bond et al. 2016). However, these descriptions of GSD severity were assigned arbitrarily, without quantitative analysis or statistical justification of the variation between categories. Given the prevalence of GSD across giraffe populations, a robust categorical description is necessary to quantify severity and to determine the ways in which GSD might affect giraffe survival and reproduction. We conducted a photogrammetry analysis of GSD from extensive photo datasets derived from camera-trapping surveys across two study sites in Tanzania. We calculated GSD severity in Ruaha National Park, where GSD is most intense (Muneza et al. 2017), and compared those classifications to rates observed in Serengeti National Park. To assess any patterns in the manifestation of GSD, we examined whether the probability of a GSD lesion appearing on one leg of a giraffe varied with the probability of GSD lesions appearing on another leg. We validated our camera trap results using high-resolution images captured from vehicle-based surveys where individual identification of giraffes was established. Our study represents the first quantification of the severity of a skin disease using photogrammetry of camera trap images. Our analytical framework is not specific to giraffes and can be used to assess externally presenting diseases affecting populations of numerous species of wildlife.

MATERIALS AND METHODS

Study areas

Ruaha National Park is located in the southern highlands of Tanzania (7°30′00″S, 35°00′00″E), where elevation ranges from 696 m to 2,171 m with an ambient temperature varying from 35 C during the day to 15 C during the night (National Bureau of Statistics 2013). With an area of 20,226 km^2, Ruaha is Tanzania's largest national park (Fig. 1) and is considered a priority landscape for large carnivore conservation (Abade et al. 2014). Recent aerial surveys show that the park is home to important populations of Masai giraffe, estimated at 3,525±980 (Tanzania Wildlife Research Institute 2015).

Serengeti National Park is located in northern Tanzania (2°20′00″S, 34°34′00″E) and covers 14,800 km^2 in the Mara-Serengeti ecosystem (Fig. 1; Reed et al. 2009). The average temperature ranges from 30 C during the day to 15 C at night, and rainfall in the ecosystem is seasonal (National Bureau of Statistics 2013). This is a migratory system where up to 1.4 million wildebeest (*Connochaetes taurinus*), zebras (*Equus* spp.), and gazelles (*Gazella* spp.) move between the Mara and Serengeti annually (Holdo et al. 2009). Serengeti National Park supports 5,886±1,221 giraffes, one of the largest populations in the country (Tanzania Wildlife Research Institute 2010).

Camera trap data

We maintained long-term camera trap systems in both Ruaha and Serengeti National parks for monitoring a variety of ecological phenomena. In Ruaha National Park, we maintained three camera trap (HyperFire HC500, Reconyx, Holmen, Wisconsin, USA) grids by placing cameras along game trails at a ~2 km^2 spacing (Cusack et al. 2015; Fig. 1). In Serengeti National Park, we maintained a large contiguous camera trap (ScoutGuard SG565 HCO Outdoor Products, Norcross, Georgia, USA) grid at a 5 km^2 resolution between 2010 and 2013, covering

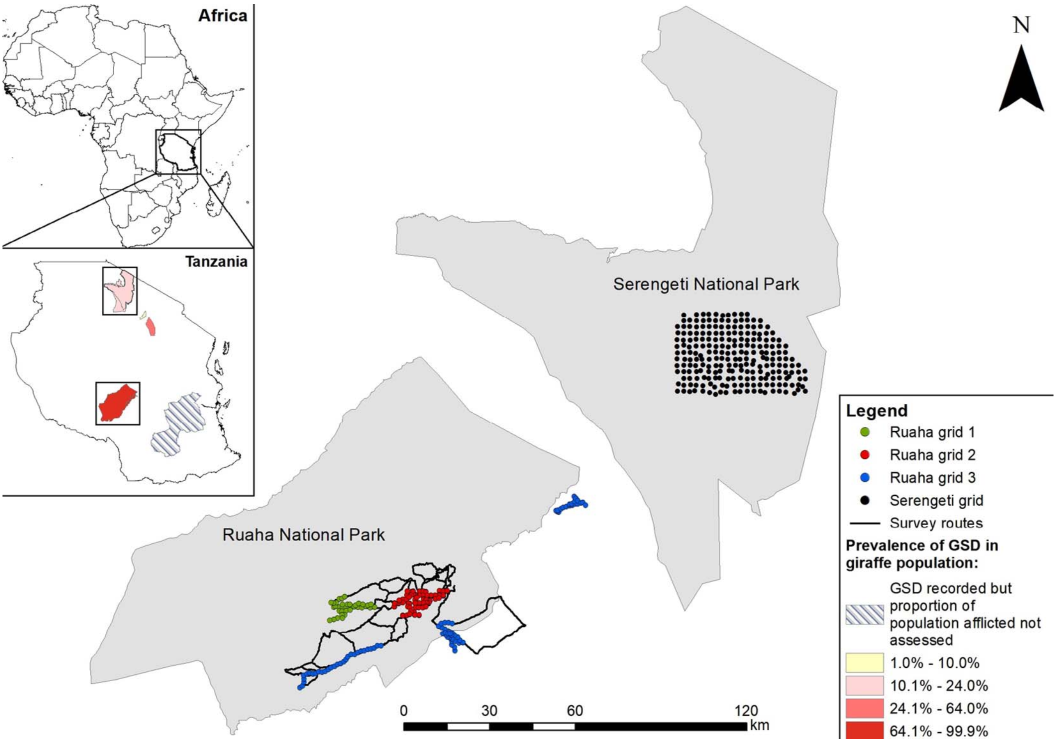

FIGURE 1. Map showing giraffe (*Giraffa camelopardalis*) study areas in Serengeti National Park in northern Tanzania and Ruaha National Park in southern Tanzania and sites where camera traps were installed to study giraffe skin disease (GSD). Camera traps of a similar grid are represented by one color. Inset map: Distribution and prevalence of GSD in conservation areas in Tanzania where the disease has been recorded.

1,125 km^2 (Swanson et al. 2015; Fig. 1). In the laboratory, we filtered all images resulting from these networks. We removed obvious duplicates (i.e., consecutive camera trap triggers of the same individual) where giraffes were detected. Next, we excluded photos that did not show the full extent of all four legs (shoulder joint to hoof) of the giraffe. Thus, our final dataset for analysis included only photos where the giraffe was close enough to the camera trap that GSD, if present, could be detected on each of the four legs and where the position of the leg afforded photogrammetric analysis (i.e., the leg was straight and no part of the leg was obscured).

Quantifying GSD severity

We used photogrammetry techniques to quantify GSD severity from the camera trap data. Using Adobe Photoshop CS6 (Adobe, San Jose, California, USA), we calculated the length of each leg (A) from the shoulder or hip joint to the carpal or tarsal joint and then to the hoof of the optimal images (Willisch et al. 2013; Fig. 2). We then measured the length of each GSD patch (a) from the proximal to the distal margin of the lesion. In cases where a giraffe had more than one patch of GSD on a single leg, we measured each individual lesion and summed the lengths of all lesions for each leg. We did not observe separate GSD lesions to vertically overlap, and, thus, the summed metric was representative of the extent of GSD for a given giraffe. We divided the total length of the lesion (a) by total length of the leg (A) to calculate the proportion (b) of the leg that was covered by GSD lesions ($b=a/A$). We calculated the approximate length of GSD lesions (B) by multiplying the proportion (b) with the average length of a giraffe's leg ($L=180$ cm) based on Christiansen (2002) such that $B=b\times 180$ cm.

Statistical analysis

We next assessed whether the probability of a GSD lesion appearing on one leg of a giraffe varied with the probability of GSD lesions appearing on another leg. To quantify the extent of statistical dependence among the proportions of GSD on each of the legs of an affected animal, we used the nonparametric Spearman's correla-

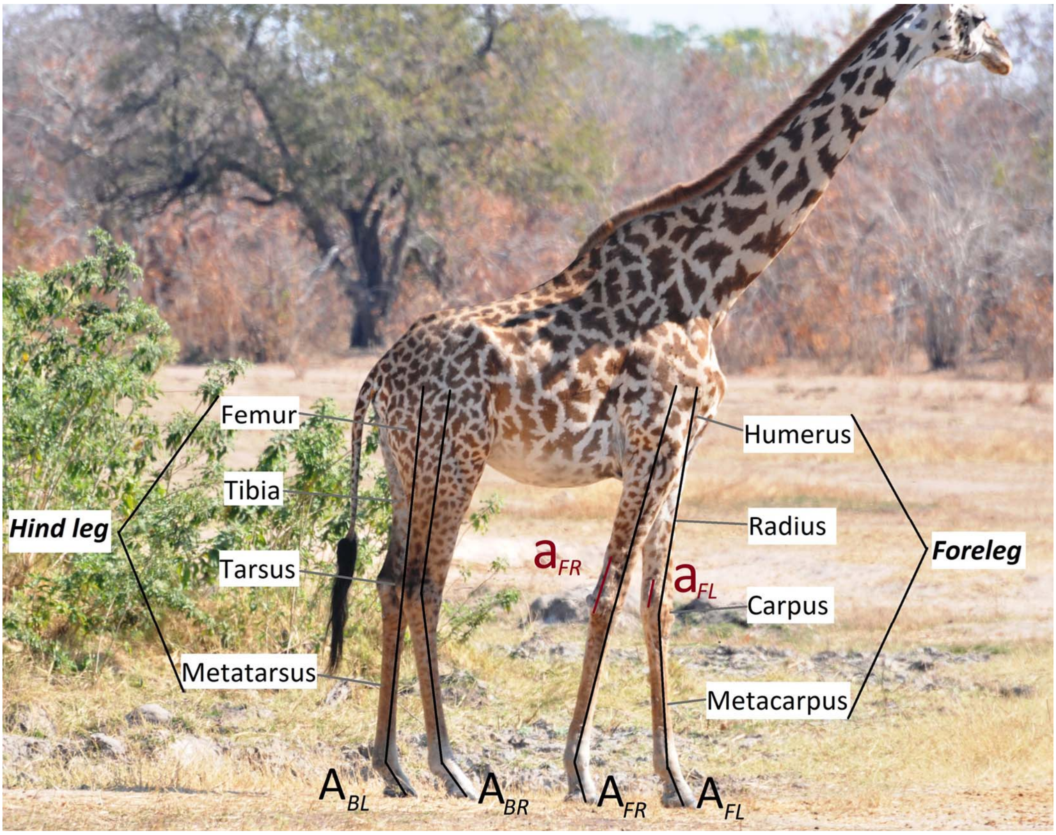

FIGURE 2. Photogrammetric measurements of giraffe (*Giraffa camelopardalis*) in Ruaha National Park, Tanzania, leg length (line A, extending from the humerus to the hoof) and giraffe skin disease lesions length (line a, extending from the proximal to the distal margin of the lesion). The proportion of the leg covered by giraffe skin disease lesions (b) was obtained by dividing the total length of line a by the total length of line A (b=a/A). FR=front right; FL=front left; BL=back left; BR=back right.

tion coefficient (r_s). We evaluated collinearity among all pairwise combinations (i.e., six possible combinations) of giraffe legs and calculated r_s using the following equation:

$$r_s = 1 - \frac{6\sum d_i^2}{n(n^2-1)}.$$

Here the Spearman's correlation coefficient r_s is calculated as a function of d_i, which is the difference between the ranks of the proportion of the leg covered by GSD lesions, and n is the number of giraffes with GSD lesions on one or more legs.

Next, we used the highest GSD proportion value recorded among all of the legs of a giraffe to categorize GSD severity. We developed these categories using the Jenks natural breaks algorithm in R statistical software (R Development Core Team 2015). The Jenks natural breaks method determines the breaks between categories (mild, moderate, or severe) by reducing the in-class variance and maximizing the variance between classes (Jenks 1967; De la Torre et al. 2015). To delineate the GSD severity categories, we used the data from Ruaha National Park, given that this park has the highest prevalence of GSD recorded (86%; Muneza et al. 2016, 2017). Thus, we consider this dataset to be most representative of the range of GSD severity. We then compared these results to those developed from the camera trap images from Serengeti National Park. We did so to facilitate a comparison of spatial variation in rates of GSD between sites within the same country.

Validation

Individual identification of giraffes was not possible from the camera trap data given that the majority of the photos included only the lower body of the giraffes. Giraffes can be readily identified when the upper body is visible (Muneza et al. 2017) but not from the legs alone. Concerned with bias resulting from the inadvertent estimation of GSD rates from the same giraffe multiple times, we compared the results of our camera-trapping analysis with an analysis derived from known giraffe data. To obtain these data, we conducted intensive vehicle-based surveys in Ruaha National Park between May and August 2015 with high-resolution photographic equipment to categorize GSD severity among individually recognizable giraffes (Fig. 1; Muneza et al. 2017). Giraffes were photographed in the field using a digital camera (Nikon D300S, Nikon, Tokyo, Japan with an autofocus-S DX Nikkor 70–300 mm f/3.5–5.6 ED VR lens) and identified to individuals using Wild-ID 1.0.0 software (Bolger et al. 2012). From the overall image dataset, we selected one optimal image per individual giraffe. We calculated individual GSD severity using the same photogrammetry techniques that we used on the camera trap images (process detailed earlier). Using the Kolmogorov-Smirnov test, we then compared the histograms of GSD severity derived from camera trap images to those created from the individually recognized giraffe data to evaluate each technique. We then examined whether the two distributions were statistically different using the following equation:

$$D_{n,n'} > c(\alpha)\sqrt{\frac{n+n'}{nn'}},$$

where $D_{n,n'}$ is the maximum difference between cumulative distribution of camera trap images (n) and individually recognized images (n'), and c=1.36 when α=0.05.

RESULTS

We obtained a total of 395 optimal camera trap images showing four entire legs of a giraffe from Ruaha National Park. Among this sample, 67.8% (268/395) were deemed suitable for photogrammetric analysis. In Serengeti National Park, we identified a total of 303 optimal images, of which 48.5% (147/303) were considered suitable for photogrammetric analysis. Additionally, in our vehicle-based photographic surveys, we captured 563 individual giraffes in Ruaha National Park, of which images from 54.17% (305/563) were deemed suitable for photogrammetric analysis.

Using the camera trap images from Ruaha National Park and Serengeti National Park, we found that lesions of GSD were more prevalent on the front legs than the back legs in both the Ruaha population (48%, 128/267) and the Serengeti population (56%, 83/148). There was no case in which a giraffe had lesions on the hind legs but not on the front legs (Fig. 3). An additional 58% (177/305) giraffes were recorded with GSD lesions on both front legs from the individually recognized giraffe dataset in Ruaha National Park (Fig. 3). Furthermore, only 10 giraffe images from the camera trap data displayed signs of GSD on more than two legs, of which 3% (9/300) were from Ruaha National Park and <1% (1/100) from Serengeti National Park (Fig. 3). There were also 3% (9/300) of giraffes from the individually recognized data that had GSD lesions on more than two legs. There were more cases of giraffes with GSD on the back legs in Ruaha National Park, where we recorded a total of five animals with lesions on all four legs (n=2 from camera trap images and n=3 from individually recognized images). In Serengeti National Park, the number of animals with signs of GSD on the front right leg (20%, 29/145) was comparable to the number of animals with GSD lesions on the front left leg (20%, 30/150). In Ruaha National Park, however, GSD lesions on the front right were more common (31%, 83/268) in camera trap images when compared to lesions on the front left leg (15%, 40/268; Fig. 3). However, among the individually recognized images from Ruaha National Park, GSD lesions were more common on the front left leg (22%, 66/300) than on the front right leg (16%, 48/300). Spearman's correlation coefficient tests showed that there was no relationship between the occurrences of GSD lesions on the legs of giraffe (Table 1). The test also revealed that there was a very weak association between the front right and front left legs (Table 1).

Using the Jenks natural breaks algorithm, we classified giraffes with 0.01% to 16.1% (1.8 to 28.8 cm) of the leg covered by GSD lesions as having mild GSD. Giraffes with 16.2% to 25% (28.9 to 45.0 cm) of the leg covered had

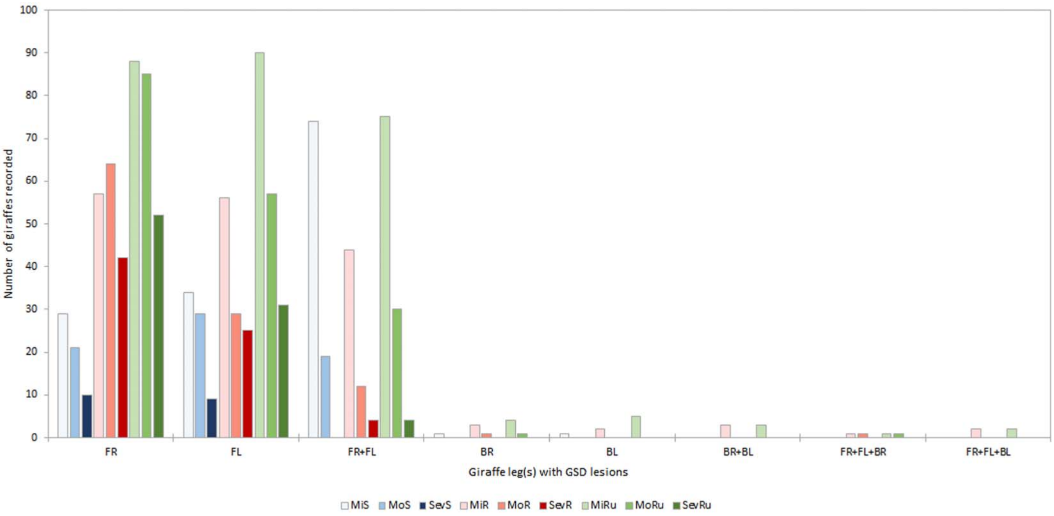

FIGURE 3. Distribution of mild, moderate and severe giraffe skin disease lesions on the legs of giraffe (*Giraffa camelopardalis*) in Ruaha National Park and Serengeti National Park, derived from camera trap images, and individually recognized giraffes in Ruaha National Park, derived from road-based photographic mark-recapture surveys. FR=front right; FL=front left; BR=back right; BL=back left; Mi=mild; Mo=moderate; Sev=severe; S=Serengeti National Park; R=Ruaha National Park (camera trap data); Ru=Ruaha National Park (digital camera data).

moderate GSD, and giraffes with lesions covering >25% (>45 cm) of the leg were classified as severe (Table 2 and Fig. 4). Histograms revealed that the predictions of the categories of GSD severity were not statistically different between the camera trap data and the individually recognized giraffe data in Ruaha National Park with $D_{n'n''}$ (0.3333) $<D$ (0.5552; Fig. 5). Furthermore, the histogram developed for the Serengeti camera trap data showed substantially lower GSD severity in Serengeti when compared to Ruaha (Fig. 5). The most severe lesion recorded in Ruaha National Park covered 66% of the front right leg of a giraffe, while the most severe case in Serengeti National Park had a lesion that covered 44% of the giraffe's front left leg (Fig. 3). Mild lesions of GSD were the most commonly observed form of the disease, and the lesions were almost evenly spread between the front right and front left legs in both Ruaha and Serengeti National parks. In Serengeti National Park, the number of severe lesions on front legs was almost equal. For instance, we recorded 10 giraffes with severe lesions on the front right leg only and nine giraffes with severe lesions on the front left leg only. There were no cases of giraffes with severe GSD lesions on both front legs in Serengeti National Park. In Ruaha National Park, severe lesions were more prevalent on the front right leg (n=42) compared to the front left, where we recorded severe lesions 25 times (Fig. 3). Additionally,

TABLE 1. Spearman's correlation coefficient (r_s) indicating the relationship between the occurrence of giraffe skin disease lesions on the legs of giraffe (*Giraffa camelopardalis*) in Ruaha National Park, Tanzania. The coefficient r_s can take values from −1 to +1, where +1 indicates a perfect positive association and −1 signifies a perfect negative association. Values closer to 0 indicate a weak relationship in the manifestation of giraffe skin disease lesions.

Legs	Spearman's correlation coefficient (r_s)
Front right+front left	−0.256
Front right+back right	0.094
Front right+back left	0.016
Front left+back left	0.102
Front left+back right	0.065
Front right and front left +back right and back left	0.101

TABLE 2. Categorization of giraffe skin disease (GSD) severity in giraffes (*Giraffa camelopardalis*) in Ruaha National Park and Serengeti National Park in Tanzania. The Jenks natural breaks used to classify the categories of giraffe skin disease severity were obtained from optimization of GSD data in Ruaha National Park.

Proportion of leg affected by GSD	Approximate length of giraffe skin disease lesions (cm)[a]	Category	Ruaha National Park		Serengeti National Park	
			Count	Proportion of sample population	Count	Proportion of sample population
0.01 to 0.16	1.8 to 28.8	Mild	102	0.38	69	0.47
0.16 to 0.25	28.9 to 45.0	Moderate	96	0.36	59	0.40
>0.25	>45.0	Severe	70	0.26	19	0.13
Total			268		147	

[a] Calculated using the average length of giraffe legs (180 cm; Christiansen 2002). Front and hind legs of giraffes have almost equal length.

three giraffes in Ruaha National Park had severe lesions on both the front right and front left leg, while such a case was not observed in Serengeti National Park.

DISCUSSION

We established a protocol for noninvasive examination of the severity of a wildlife skin disease using camera trap images and photogrammetry techniques. We did so by assessing an emergent disease affecting giraffe populations in a region of the world (Tanzania) that is a hotspot for this disease (Muneza et al. 2016). To date, most studies report only the occurrence of GSD with severity assigned using arbitrary demarcations between categories (Kalema 1996; Epaphras et al. 2012; Bond et al. 2016). For example, in Ruaha National Park, more than half of the population (51.7%) was estimated to have GSD lesions that were deemed to be severe (>16 cm; Epaphras et al. 2012). This technique for estimating GSD severity, which requires close observation of affected animals, is not only laborious but also narrow in the spatial extent

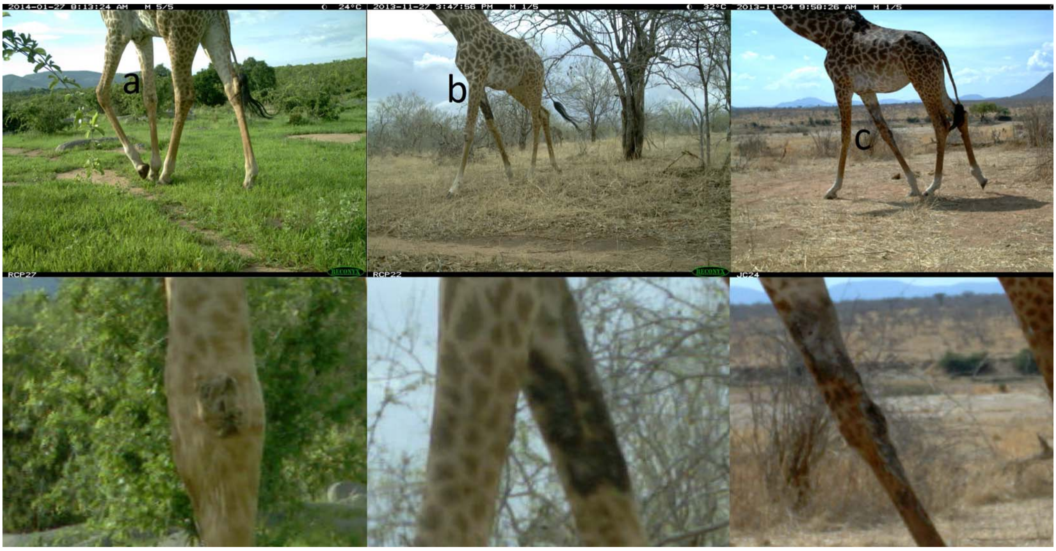

FIGURE 4. Illustration of the three categories of giraffe skin disease severity on giraffe (*Giraffa camelopardalis*) legs in Ruaha National Park, Tanzania: mild (a: 6% of leg affected), moderate (b: 25% of leg affected), and severe (c: 47% of leg affected).

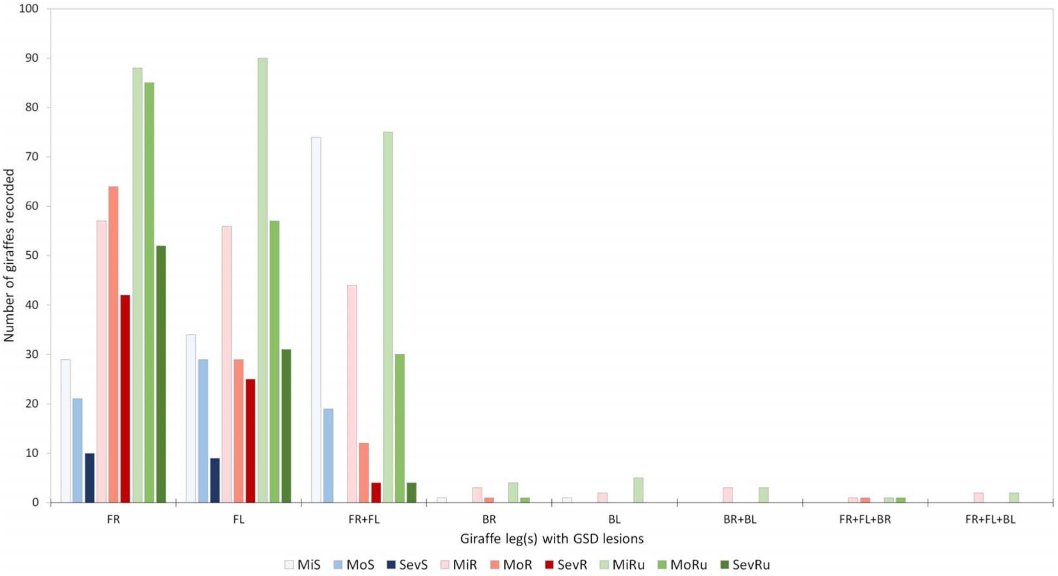

FIGURE 5. Distribution histogram of the proportion of giraffe (*Giraffa camelopardalis*) leg affected by giraffe skin disease (GSD) in Ruaha National Park and Serengeti National Park. There is no statistically significant difference ($D_{n'n''}$ [0.3333]<D [0.5552]) between images from known giraffe and camera trap images of giraffe indicating distribution of GSD severity categories is similar. FR=front right; FL=front left; BR=back right; BL=back left; Mi=mild; Mo=moderate; Sev=severe; S=Serengeti National Park; R=Ruaha National Park (camera trap data); Ru=Ruaha National Park (digital camera data).

across which it can be applied. Particularly with respect to emergent diseases, it is necessary to assess patterns of disease ecology across large scales with information returned in a timely fashion. Our analysis demonstrated the utility of large-scale camera-trapping systems and photogrammetry techniques in providing assessments of skin disease severity. These approaches are noninvasive, can be rapidly deployable, and are applicable to a variety of species. With large repositories of camera trap data becoming increasingly common (Kays et al. 2015), it will be possible to examine spatiotemporal trends in the distribution, prevalence, and severity of disease that present on the derma of affected animals.

Our results demonstrated that in both Ruaha and Serengeti National parks, most cases of GSD detected via our camera trap systems were mild. Despite the fact that 86% of the giraffe population in Ruaha National Park has GSD, the majority of these animals have a mild form of the disease. We also found that rates of moderate GSD were approximately comparable between Ruaha and Serengeti National parks (36% in Ruaha National Park and 40% in Serengeti National Park). However, Ruaha National Park had rates of severe GSD that were twice as high as in Serengeti National Park. As much as 86% of the giraffe population in Ruaha National Park has GSD (Muneza et al. 2017), followed closely by Tarangire National Park, where 63% of the population is affected, and then Serengeti National Park with 23% of the population (Muneza et al. 2016). Tarangire is located between Ruaha and Serengeti National parks, which suggests that GSD might be affected by spatial or environmental factors (Bond et al. 2016; Lee and Bond 2016). More specifically, the declining GSD prevalence with distance from Ruaha National Park in Tanzania supports a theory that GSD in Tanzania could be emanating from Ruaha National Park outward. However, additional research on these different populations would need to be done to fully evaluate this prospect.

We could not find any obvious relationship in GSD manifestation among the different legs of Masai giraffe. Spearman's correlation coefficient (r_s) showed that there was no statistical dependence in the manifestation of GSD. This meant that the probability of a lesion appearing on one leg of a giraffe did not vary with the probability of lesions appearing on another leg. We searched for associations of six different combinations of giraffe legs but found only one weak negative association for one combination (front right and front left). This was particularly interesting given that GSD in Masai giraffes commonly manifests on the forelegs of affected giraffe (Epaphras et al. 2012; Lee and Bond 2016; Muneza et al. 2016). While we did not identify any order or pattern of GSD manifestation, we noted that lesions were much more prevalent on both forelegs when compared to hind legs (Fig. 3). This could possibly have been because GSD has been suggested to be caused by filarial worms and further complicated by secondary fungal infections (Epaphras et al. 2014; Lee and Bond 2016). Filarial worms are mostly transmitted by biting insects, and giraffes have a long tail that can deter insects from hind legs whereas the forelegs are more exposed (Siegfried 1990). Future studies intending to collect tissue samples to better understand the epidemiology of GSD should focus on the forelegs and survey for biting insects.

It remains unclear whether GSD severity negatively affects the survival and reproduction of affected animals. Giraffes with severe forms of GSD have been suggested to move with increased difficulty, potentially altering their vulnerability to predators (Epaphras et al. 2014). However, in these instances, GSD severity was assigned arbitrarily. Via the application of photogrammetric techniques to camera trap data we quantitatively derived an index of GSD severity. Providing that camera trap data are available, these techniques can be readily applied to determine temporal and/or spatial variation in skin diseases in animals with identifiable features. We suggest that these techniques, in combination with focal animal observation, can be a means by which to assess the consequences of skin disease severity on wildlife ecology.

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LITERATURE CITED

Abade L, Macdonald DW, Dickman AJ. 2014. Assessing the relative importance of landscape and husbandry factors in determining large carnivore depredation risk in Tanzania's Ruaha landscape. *Biol Conserv* 180: 241–248.

Berger J. 2012. Estimation of body-size traits by photogrammetry in large mammals to inform conservation. *Conserv Biol* 26:769–777.

Blehert DS, Hicks AC, Behr M, Meteyer CU, Berlowski-Zier BM, Buckles EL, Coleman JTH, Darling SR, Gargas A, Niver R, et al. 2009. Bat white-nose: An emerging fungal syndrome pathogen? *Science* 323: 227.

Bolger DT, Morrison TA, Vance B, Lee D, Farid H. 2012. A computer-assisted system for photographic mark-recapture analysis. *Methods Ecol Evol* 3:813–822.

Bond ML, Strauss MKL, Lee DE. 2016. Soil correlates and mortality from giraffe skin disease in Tanzania. *J Wildl Dis* 52:953–958.

de Bruyn PJN, Bester MN, Carlini AR, Oosthuizen WC. 2009. How to weigh an elephant seal with one finger: A simple three-dimensional photogrammetric application. *Aquat Biol* 5:31–39.

Carter KD, Brand R, Carter JK, Shorrocks B, Goldizen AW. 2013. Social networks, long-term associations and age-related sociability of wild giraffes. *Anim Behav* 86:901–910.

Christiansen PER. 2002. Locomotion in terrestrial mammals: The influence of body mass, limb length and bone proportions on speed. *Zool J Linn Soc* 136:685–714.

Cusack JJ, Dickman AJ, Rowcliffe JM, Carbone C, Macdonald DW, Coulson T. 2015. Random versus game trail-based camera trap placement strategy for monitoring terrestrial mammal communities. *PLoS One* 10:e0126373.

De la Torre A, Bosch J, Iglesias I, Muñoz MJ, Mur L, Martínez-López B, Martínez M, Sánchez-Vizcaíno JM. 2015. Assessing the risk of African swine fever introduction into the European Union by wild boar. *Transbound Emerg Dis* 62:272–279.

Durban JW, Fearnbach H, Barrett-Lennard LG, Perryman WL, LeRoi DJ. 2015. Photogrammetry of killer whales using a small hexacopter launched at sea. *J Unmanned Veh Syst* 3:131–135.

Epaphras AM, Karimuribo ED, Mpanduji DG, Meing'ataki GE. 2012. Prevalence, disease description and epidemiological factors of a novel skin disease in giraffes (*Giraffa camelopardalis*) in Ruaha National Park, Tanzania. *Res Opin Anim Vet Sci* 2:60–65.

Epaphras AM, Mwamengele GL, Misinzo G, Mngumi BE. 2014. *Investigation report on giraffe skin disease in Ruaha National Park*. Tanzania National Parks Authority, Iringa, Tanzania, 38 pp.

Frick WF, Pollock JF, Hicks AC, Langwig KE, Reynolds DS, Turner GG, Butchkoski CM, Kunz TH. 2010. An emerging disease causes regional population collapse of a common North American bat species. *Science* 329:679–682.

Giraffe Conservation Foundation. 2013. *Africa's giraffe: A conservation guide*. Black Eagle Media, Western Cape, South Africa, 24 pp.

Hayward MW, Henschel P, O'Brien J, Hofmeyr M, Balme G, Kerley GIH. 2006. Prey preferences of the leopard (*Panthera pardus*). *J Zool* 270:298–313.

Hayward MW, Kerley GIH. 2005. Prey preferences of the lion (*Panthera leo*). *J Zool* 267:309–322.

Hayward MW, Kerley GIH. 2008. Prey preferences and dietary overlap amongst Africa's large predators. *South African J Wildl Res* 38:93–108.

Hiby L, Lovell P, Patil N, Kumar NS, Gopalaswamy AM, Karanth KU. 2009. A tiger cannot change its stripes: Using a three-dimensional model to match images of living tigers and tiger skins. *Biol Lett* 5:383–386.

Holdo RM, Holt RD, Fryxell JM. 2009. Opposing rainfall and plant nutritional gradients best explain the wildebeest migration in the Serengeti. *Am Nat* 173: 431–445.

Jenks GF. 1967. The data model concept in statistical mapping. *Int Yearbook Cart* 7:186–190.

Jones ME, Jarman PJ, Lees CM, Hesterman H, Hamede RK, Mooney NJ, Mann D, Pukk CE, Bergfeld J, McCallum H. 2007. Conservation management of Tasmanian devils in the context of an emerging, extinction-threatening disease: Devil facial tumor disease. *Ecohealth* 4:326–337.

Kalema G. 1996. *Investigation of a skin disease in giraffe in Murchison Falls National Park*. Uganda National Parks, Kampala, Uganda, 5 pp.

Karimuribo ED, Mboera LEG, Mbugi E, Simba A, Kivaria FM, Mmbuji P, Rweyemamu MM. 2011. Are we prepared for emerging and re-emerging diseases? Experience and lessons from epidemics that occurred in Tanzania during the last five decades. *Tanzan J Health Res* 13 (5 Suppl 1):387–398.

Kays R, Crofoot MC, Jetz W, Wikelski M. 2015. Terrestrial animal tracking as an eye on life and planet. *Science* 348:aaa2478.

Lee DE, Bond ML. 2016. The occurrence and prevalence of giraffe skin disease in protected areas of northern Tanzania. *J Wildl Dis* 52:753–755.

McCallum H, Jones M, Hawkins C, Hamede R, Lachish S, Sinn DL, Beeton N, Lazenby B. 2009. Transmission dynamics of Tasmanian devil facial tumor disease may lead to disease-induced extinction. *Ecology* 90:3379–3392.

McCallum H, Tompkins DM, Jones M, Lachish S, Marvanek S, Lazenby B, Hocking G, Wiersma J, Hawkins CE. 2007. Distribution and impacts of Tasmanian devil facial tumor disease. *Ecohealth* 4: 318–325.

Meise K, Mueller B, Zein B, Trillmich F. 2014. Applicability of single-camera photogrammetry to determine body dimensions of pinnipeds: Galapagos sea lions as an example. *PLoS One* 9:e101197.

Muller Z, Bercovitch F, Brand R, Brown D, Brown M, Bolger D, Carter K, Deacon F, Doherty JB, Fennessy J, et al. 2016. *Giraffa camelopardalis*. In: *International Union for Conservation of Nature red list of threatened species*. 2016:e.T9194A109326950. https://www.iucnredlist.org/species/9194/109326950. Accessed April 2017.

Muneza AB, Linden DW, Montgomery RA, Dickman AJ, Roloff GJ, Macdonald DW, Fennessy JT. 2017. Examining disease prevalence for species of conservation concern using non-invasive spatial capture–recapture techniques. *J Appl Ecol* 54:709–717.

Muneza AB, Montgomery RA, Fennessy JT, Dickman AJ, Roloff GJ, Macdonald DW. 2016. Regional variation of the manifestation, prevalence, and severity of giraffe skin disease: A review of an emerging disease in wild and captive giraffe populations. *Biol Conserv* 198:145–156.

National Bureau of Statistics. 2013. *Tanzania in figures 2012*. Ministry of Finance and Economic Affairs, Dar es Salaam, Tanzania, 81 pp. https://www.nbs.go.tz/nbstz/index.php/english/tanzania-in-figures/229-tanzania-in-figures-2012. Accessed December 2015.

O'Brien TG, Kinnaird MF. 2011. Density estimation of sympatric carnivores using spatially explicit capture—Recapture methods and standard trapping grid. *Ecol Appl* 21:2908–2916.

R Development Core Team. 2015. *R: A language environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. https://cran.r-project.org/bin/windows/base/. Accessed December 2015.

Reed DN, Anderson TM, Dempewolf J, Metzger K, Serneels S. 2009. The spatial distribution of vegetation types in the Serengeti ecosystem: The influence of rainfall and topographic relief on vegetation patch characteristics. *J Biogeogr* 36:770–782.

Rothman JM, Chapman CA, Twinomugisha D, Wasserman MD, Lambert JE, Goldberg TL. 2008. Measuring physical traits of primates remotely: The use of parallel lasers. *Am J Primatol* 70:1191–1195.

Rowcliffe JM, Field J, Turvey ST, Carbone C. 2008. Estimating animal density using camera traps without the need for individual recognition. *J Appl Ecol* 45: 1228–1236.

Siegfried WR. 1990. Tail length and biting insects of ungulates. *J Mamm* 71:75–78.

Skerratt LF, Berger L, Speare R, Cashins S, McDonald KR, Phillott AD, Hines HB, Kenyon N. 2007. Spread of chytridiomycosis has caused the rapid global decline and extinction of frogs. *Ecohealth* 4:125–134.

Swanson A, Kosmala M, Lintott C, Simpson R, Smith A, Packer C. 2015. Snapshot Serengeti, high-frequency annotated camera trap images of 40 mammalian species in an African savanna. *Sci Data* 2:150026.

Tanzania Wildlife Research Institute. 2010. *Aerial survey in the Serengeti ecosystem, dry season, 2010.* TAWIRI Aerial Survey Report. Tanzania Wildlife Research Institute, Arusha, Tanzania, 52 pp.

Tanzania Wildlife Research Institute. 2015. *Wildlife survey in the Ruaha-Rungwa ecosystem, dry season 2015.* TAWIRI Wildlife Survey Report. Tanzania Wildlife Research Institute, Arusha, Tanzania, 73 pp.

Voyles J, Young S, Berger L, Campbell C, Voyles WF, Dinudom A, Cook D, Webb R, Alford RA, Skerratt LF, et al. 2009. Pathogenesis of chytridiomycosis, a cause of catastrophic amphibian declines. *Science* 326:582–585.

Waite JN, Schrader WJ, Mellish JAE, Horning M. 2007. Three-dimensional photogrammetry as a tool for estimating morphometrics and body mass of Steller sea lions (*Eumetopias jubatus*). *Can J Fish Aquat Sci* 64:296–303.

Willisch CS, Marreros N, Neuhaus P. 2013. Long-distance photogrammetric trait estimation in free-ranging animals: A new approach. *Mamm Biol* 78: 351–355.

Zheng X, Owen MA, Nie Y, Hu Y, Swaisgood RR, Yan L, Wei F. 2016. Individual identification of wild giant pandas from camera trap photos—A systematic and hierarchical approach. *J Zool* 300:247–256.

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