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USE OF UNMANNED AERIAL VEHICLES TO QUANTIFY SOCIAL AFFILIATIONS IN BEEF CALVES

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USE OF UNMANNED AERIAL VEHICLES TO QUANTIFY SOCIAL AFFILIATIONS IN BEEF CALVES

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JUSTIN TERRANCE MUFFORD

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This thesis has been accepted as conforming to the required standards by:

John S. Church (Ph.D.), Thesis Supervisor, Dept. Natural Resource Sciences

Garrett Whitworth (Ph.D.), Examining Committee member, Dept. Natural Resource Sciences

Matt Reudink (Ph.D.), Examining Committee member, Dept. Biological Sciences

Nancy Flood (Ph.D.), Examining Committee member, Dept. Biological Sciences

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ABSTRACT

We developed a novel method to quantify cow-calf social affiliations by using unmanned aerial vehicles (UAVs) to quantify the distance between pairs of individuals in a herd. Using two UAVs equipped with video-capable digital cameras, as well as photogrammetry and image analysis software, we measured the distance between cow-calf pairs. We hypothesized that this distance can be accurately measured by UAVs and has the potential to provide valuable information in studies of animal behaviour and welfare. Twelve cow-calf pairs were uniquely identified with the use of penning tags and coloured fabric squares glued to their backs. Aerial videos of the calves held with their dams in a pasture were made over four days using UAVs. Recordings were made during two periods on most days of study: Daytime (Day) and Evening (Eve). Calves were acclimated to the UAVs by flying one UAV intermittently at distance of 10 m away from the calf on the days before experimental recording began. We used two UAVs to video-capture the following: (1) the location of all individuals (UAV flown at 100 m) and; (2) the identity of cow-calf pairs (UAV flown at 15 - 30 m). Still-images extracted from the UAV-acquired video screenshots were used to produce orthomosaics using Agisoft Photoscan software to correct geometric distortions from the original images. The orthomosaics captured all of the cows and calves in a single image, from which we measured the distance between calves and their dams and the distance between calves and non-related cows in the herd. We constructed a mixed model to test the effect of time period and cow-calf relationship (related or non-related) on cow-calf distance. Time period and cow-calf relationship each had a statistically significant effect ($F_{1,849}$ = 101.79 and $F_{1,849}$ = 26.75, respectively, $P < 0.001$) on the distance between cows and calves, but there was no significant interaction between these variables ($F_{1,849}$ = 1.35, $P = 0.245$). The mean distance between calves and their dams ($\bar{X}$ = 43.8 m, SD = 24 m) was smaller than that between calves and non-related cows ($\bar{X}$ = 55.6 m, SD = 28 m). The mean cow-calf distance was smaller in the daytime ($\bar{X}$ = 39.8 m, SD = 15 m) than in the evening ($\bar{X}$ = 84.3 m, SD = 24 m). Distance measurements were tested for accuracy using reference lengths that were measured in the field; the mean difference between our software-measured length and the true length was 0.9 ± 0.7 m (mean and standard deviation). Our novel and non-invasive method appears to be sufficiently accurate and precise to study social behaviour in beef cattle in a field setting.

Thesis Supervisor: Dr. John Scott Church

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INTRODUCTION

Cattle raised by commercial producers form gregarious and complex social structures (Sowell et al. 1999; Schein & Fohrman 1955). Understanding the social behaviour of cattle raised in these commercial settings is important to optimize beef cattle production. For example, pregnant cows prefer to isolate themselves from the herd in the hours prior to giving birth (Finger et al. 2014). Commercial production systems that do not provide enough space for birthing cows risk interfering with important bonding behaviours, which occur optimally in isolation from the rest of herd. This could result in the breakdown of maternal behaviour, including rejection of the calf, which reduces its ability to grow (von Keyserlingk & Weary 2007). Furthermore, social dominance plays a large role in feeding behavior; overcrowding and improper grouping of cattle can negatively impact feeding behaviour and therefor production (Grant & Albright 2001; Phillips & Rind 2001). While there are a multitude of social behaviours that can be studied in cattle, the focus of this study was social affiliations. Social affiliations, (aka social contacts, social interactions, and social associations) are fine-scale behavioural interactions between two or more individuals within a herd (e.g., cow-calf, cow-bull), which are often of interest to cattle producers (O'Neill et al. 2014). Social affiliations have been investigated both quantitatively and qualitatively for decades, by using field observations and with the use of technology such as video cameras, radio telemetry and global positioning system (GPS) devices.

For behavioural research purposes, cattle can be fitted with collars equipped with global positioning system (GPS) or global navigation satellite system (GNSS) devices, to obtain their locations at consistent sampling frequencies (Handcock et al. 2009), which depend on the ecological and/or behavioural questions being addressed (Anderson et al. 2012). The accuracy of position measurement made using GPS varies between different models of collars and the data analysis tools used to manage the raw GPS co-ordinates. The accuracy ranges from 1 or 2 m to 15 m (reviewed by Anderson et al. 2013). The accuracy has also been shown to be affected by the topography and habitat of the area in which the GPS is used (Lewis et al. 2007).

In the past, cattle have also been fitted with collars equipped with ultra-high frequency (UHF) radio devices to observe fine-scale social interactions (Swain & Hurley 2007). These devices, known as contact loggers or proximity loggers, emit unique radio frequencies, and receive emissions from other devices, to log the frequency and duration of close contacts between two individual animals. This method of quantifying social affiliations has been commonly employed to study various aspects of social behaviour, such as interactions with other species (Drewe et al. 2012), and social preferences (Patison et al. 2010; Swain & Hurley 2007), as well as to identify cows in estrus based on cow-bull contacts (O'Neill et al. 2014). Cow-calf social affiliations have also been quantified manually, by visually estimating the distances between individuals (Daleszczyk et al. 2004) and by estimating the coordinates of individual animals with the use of field markers (Hirata et al. 2003) and references to field maps (Veissier et al. 1990). These measurements have been used to study social preferences, maternal behaviour, and the dependence of calves to their dams (Hirata et al. 2003; Veissier et al. 1990).

Studying social behaviour using GPS collars and radio telemetry technology has been shown to be reliable; however, these devices can be costly and their use requires a high level of expertise. Furthermore, problems associated with these devices include limited battery life, low accuracy (Anderson et al. 2013), and a tendency to be damaged by weather and/or the wearer. Manual observation has been proven to be cost-effective; however, observers in the field can impact the behaviour of cattle thus affecting the validity of results. It has been demonstrated in standardized behavioural tests that humans, whether they are stationary or moving, influence cattle behaviour (reviewed by Waiblinger et al. 2006). Indeed, cattle, among other farm animals, develop relationships with humans such that the animals can perceive human interaction as positive, neutral, or negative, depending on their previous experiences and their underlying personality traits (reviewed by Waiblinger et al. 2006). As an alternative to these techniques, we developed a novel method to quantify cow-calf social affiliations using unmanned aerial vehicles (UAVs) to determine the position of individuals in the field, using photogrammetry techniques and photo editing software that is efficient and non-invasive.

Over the last decade, remarkable technological advances have been made in the development of UAVs (Whitehead et al. 2014a; Whitehead et al. 2014b). UAVs are desirable for research because of their low operational cost, ease of use, and flexibility in difficult terrain and adverse weather conditions; they can be equipped with a variety of sensors (e.g., hyperspectral, multispectral, infrared), produce little noise, reduce the risk of dangerous interactions with study subjects, and eliminate the effect of human presence on animal behaviour (Pajares 2015; Moreland et al. 2015; Matese et al. 2015; Klemas 2015; Koh & Wich 2012). These factors have led to a substantial increase in the use of unmanned aerial vehicles in wildlife monitoring (reviewed by Linchant et al. 2015), studies of wildlife ecology (reviewed by Anderson & Gaston 2013), and agriculture (reviewed by Zhang et al. 2012). UAVs have been used to survey an incredibly diverse array of taxa including songbirds (e.g., *Spizella passerina*) (Wilson et al. 2017), seabirds (e.g., *Fregata ariel*) (Hodgson et al. 2016), seals (*Halichoerus grypus*) (Seymour et al. 2017), humpback whales (*Megaptera novaeangliae*) (Hodgson et al. 2017), elephants (*Loxodonta africana*) (Vermeulen et al. 2013), dugongs (*Dugong dugon*) (Hodgson et al. 2013) and black rhinos (*Diceros bicornis*) (Mulero-Pazmany et al. 2014). Recently, they have also been used to study animal behaviour. In 2017, Hodgson *et al.* used quadcopters to follow humpback whales near the coast of Australia. In this study, the drones were automated to follow pods of whales, allowing the researchers to observe the travelling, diving and grouping of pods. Researchers at the USGS Alaska Science Centre flew small unmanned aircraft over sea otter habitat to observe their foraging behaviour without disturbing them (UAF 2017). UAVs have also been employed in the cattle industry to count cattle in large feedlots with a reasonable level of accuracy, using both video cameras (Chamoso et al. 2014) and thermal cameras (Whitehead et al. 2014b). In addition, UAVs have been used to predict feed intake in cattle kept in small feeding pens (Nyamuryekung'e et al. 2016). Currently, we are the first to combine the use of UAVs and photogrammetry to study the fine-scale social behaviour (i.e., social affiliations) of cattle in a field setting.

Photogrammetry is a set of techniques used to obtain quantitative and qualitative data on the position of objects and the spaces between them from photographs (Ey-Chmielewska et al. 2015). One common application of photogrammetry is the construction of 2-dimensional and 3-dimensional topographic maps, which have been widely used in agriculture to obtain information on crop health (reviewed by Candiago et al. 2015). Another common application of photogrammetry is the construction of an orthomosaic, a 2-dimensional overhead-view image constructed from multiple overlapping photos through a technique called orthorectification, which corrects for geometric distortion caused by the nature of aerial photography (Laliberte et al. 2010; Afek & Brand 1998). Geometric distortion in photos alters the true relative positions of points on the image such that the length of an object, the length of a given area, or the distance between different points on the image, can appear longer or shorter than it actually is. Distance and angle of the camera (i.e., the perspective from which a photo is taken) can greatly distort the relative positions between objects in an image, especially an aerial photograph captured at a tilted angle, rather than perfectly vertical (tilt displacement) (Figure 1) (Verhoeven et al. 2012). Furthermore, the magnitude of distortion worsens as the altitude at which the photo is being taken increases. A tilt in the camera causes the distance between two points on the image to appear longer or shorter than they actually are because when a camera sensor receives light at an angle (Figure 1), the light rays hitting the camera sensor are displaced, which results in a distorted image. The higher the altitude of an angled camera, the greater the displacement of light rays on the camera sensor.

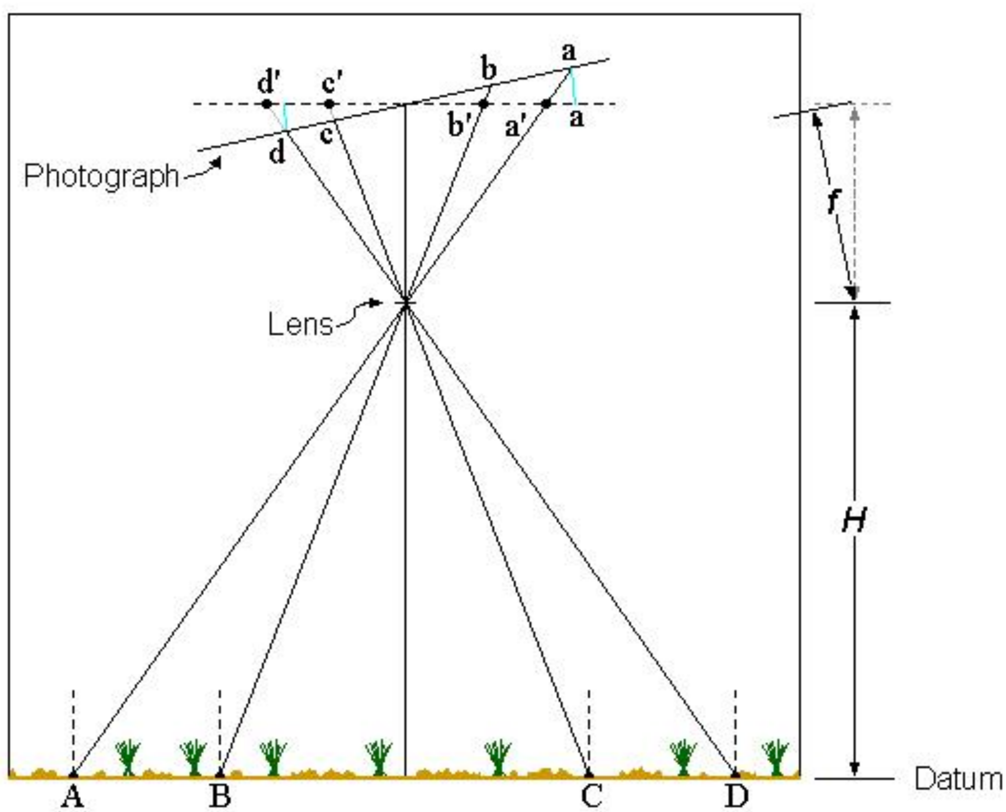

Figure 1. A diagram of a camera sensor receiving light rays at angle, taken from (Trac 2010a). This diagram illustrates how an angled camera results in tilt displacement. The distance between A' and B' is equal to the distance between C' and D' but this is distorted on the camera sensor as shown by this diagram.

The topography of an area can also distort the relative positions between two different points on a photograph (Figure 2). This is known as relief displacement.

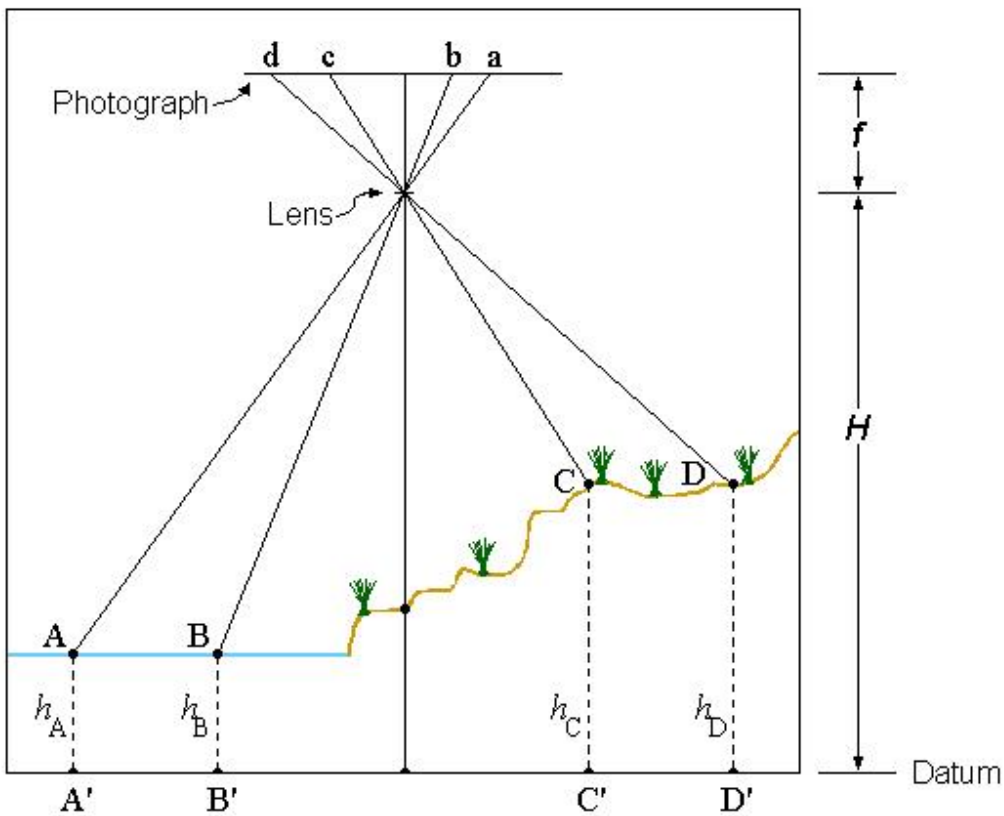

Figure 2. A diagram of light rays entering a light sensor on a camera, taken from (Trac 2010b). This schematic is an illustration of relief displacement. The distance between A' and B' is equal to the distance between C' and D' but this is distorted on the camera sensor as shown by this diagram.

The orthorectification process involves using software that builds a 3D model of a given area from 2D aerial photos. Mathematical computation is used to determine 3D coordinates from multiple photos of overlapping images. The software then uses the 3D model to correct for geometric distortions to build an accurate 2D orthomosaic. To our knowledge, few studies combine the use of UAVs and photogrammetry techniques for animal conservation and management purposes. Seymour *et al.* (2017) developed a method for automated detection and enumeration of grey seal (*Halichoerus grypus*) colonies. This method consists first, of using a UAV to capture infrared and RGB photos at designated intervals on an autonomous flight path; then these photos are orthorectified and merged to create a single orthomosaic image; this image is further processed by running algorithms programmed for automated detection and enumeration of individuals and automated discrimination between pups and adults. Durban *et al.* (2015) piloted a technique using UAVs for collecting anatomical information on killer whales (*Orcinus orca*). In this pilot project, a UAV was deployed from the deck of a boat and used to capture overhead photos of the whales; these photos were calibrated for measuring the length of the backs of individuals using computer software.

The objective of this study was to develop and examine the use of a novel, non-invasive method to quantify social affiliations of beef calves (*Bos taurus*) using UAVs and photogrammetry techniques. We hypothesize that our method can be used to quantify the distance between cow-calf pairs in a field setting with a sufficient level of accuracy and precision to study behavioural interactions between individual animals.

METHODS & MATERIALS

Experimental Design

Twelve Angus/cross beef cows (*Bos taurus)* and their single, 4-month-old calves were studied over a 4-day period during the month of June, 2016 at the Agriculture & Agri-Food Canada (AAFC) Lethbridge Research Centre, located near the city of Lethbridge, AB, Canada, while the cow-calf pairs were on pasture. Each cow-calf pair was uniquely identified with the use of penning tags (Wheel'n'Tree Enterprises, www.penningsupplies.com) and coloured fabric squares (22.9cm x 50.4cm) glued to their backs with tagging cement. We collected aerial data twice per day in two different time periods: Daytime (Day) and Evening (Eve) for a total of six time periods throughout the study (poor weather precluded data collection in two of the eight possible time periods). The six time periods are designated Day 1 Daytime, Day 2 Daytime, Day 2 Evening, Day 3 Daytime, Day 4 Daytime, and Day 4 Evening. The Daytime period was between 10:00 and 16:30 hours, while Evening period was between 17:30 and 21:30 hours. We attempted to collect data every 15 minutes within each time period, but poor weather prevented the collection of data at certain times; as a result, a different number of sampling points (i.e., times at which samples were taken) was included in each time period: Day 1 Daytime, 7 points; Day 2 Daytime, 17 points; Day 2 Evening, 12 points; Day 3 Daytime, 13 points; Day 4 Daytime, 14 points; Day 4 Evening, 13 points (total = 76 sampling points). At each sampling point, we measured the distance between the calves and their dams as well as the distance between the calves and each of the other 11 cows in the herd. Thus, at each sample point, we made 12 distance measurements for the calf-dam pairs and 122 distance measurements between calves and non-related cows. We then calculated the mean calf-dam distance and the mean distance between calves and non-related cows at each time point.

This made two groups according to calf-cow relationship, which we called “Calf-Dam” and “Calf-Other”. The four daytime periods (51 sample points) and the two evening periods (25 sample points) made a Daytime (“Day”) group and Evening (“Eve”) group, respectively. We compared the mean distance between cow-calf pairs by cow-calf relationship (i.e., Calf-Dam vs Calf-Other) and by time period (i.e., Day vs Eve).

Habituation to UAVs

Two Phantom 4 DJI drones (Dà-Jiāng Innovations Science and Technology Co., Ltd) equipped with 12-megapixel video cameras were used in the study. Three days prior to the data collection, we allowed cattle to acclimatize to the UAVs hovering above and remaining stationary, in front of, to the side of, and behind them, at a height of 10 m. In addition, we allowed cattle to acclimatize to the UAVs flying past them up to speeds of 65km/hr at a height of 30 m. On the first day of the habituation period, we observed that each individual showed reactions to the drone when the UAV was within 10 m. The behaviours we observed included raising their head directly upwards to look at the UAV when it was hovering in front and above the individual at a height of 10 m. We also observed cattle raising their heads and turning their heads towards the side of their flank to look at the UAV when it was hovering behind them or at a lateral distance of up to 10 m and a height of 10 m. After repeating this for three days, we observed that none of the cattle showed any observable behavioural response to the UAVs when they were hovering within 10 m of them (in any direction). We did not observe cattle responding to UAVs flying past them at a height of 30m throughout the habituation period.

Field Data Collection

At each of the 76 sampling points throughout the data collection period, we flew both DJI Phantom 4 UAVs simultaneously, but at different altitudes. One pilot flew at an altitude of 100 m and the other pilot flew at an altitude of between 15 and 30 m. Both pilots video recorded the herd at 4K resolution and 24 frames per second (fps). The video recorded at 100 m was used to generate a composite image of the entire herd and the video recorded at an altitude varying between 15 and

30 m was used to identify each individual cow and calf on the composite images (Figure 3) (See data acquisition for more details).

Figure 3. A picture of calves and cows obtained by taking a screenshot of video recorded by a Phantom 4 drone at an altitude of 20 m. Cows and calves were identified by coloured-felt and numbered penning tags glued to their back with tagging cement. Each calf and its dam had the same numbered tag and colour of fabric glued on their backs. Twelve different numbers and colours were assigned to the herd to distinguish each pair. For example, in this photo the Calf-Dam pair that possesses the combination of the green felt fabric and penning tag #1 is distinguished from the other Calf-Dam pair that possesses the magenta felt fabric and penning tag #3. The combination of colour and number was necessary since sometimes the glare from the sunlight made it difficult to identify the cattle by penning tag number alone.

Data Acquisition

Measuring cow-calf distances

At every sampling time point, we took screenshots of the collected video to obtain jpeg images of the cattle herd. In most of the videos, the herd was too widely spaced to capture every individual in a single frame. Thus, we used multiple, overlapping screenshots to capture the entire herd, orthorectifying the photos together to generate a single, orthorectified image (an orthomosaic) using photogrammetry software (Agisoft Photoscan Pro) (Figure 4a-d). We also did this when the herd was tightly spaced together and didn't require multiple photos since the orthorectification process corrects for tilt displacement and relief displacement (geometric distortions of photos that are caused by the camera aspect and the terrain of the area in which the photos are being taken).

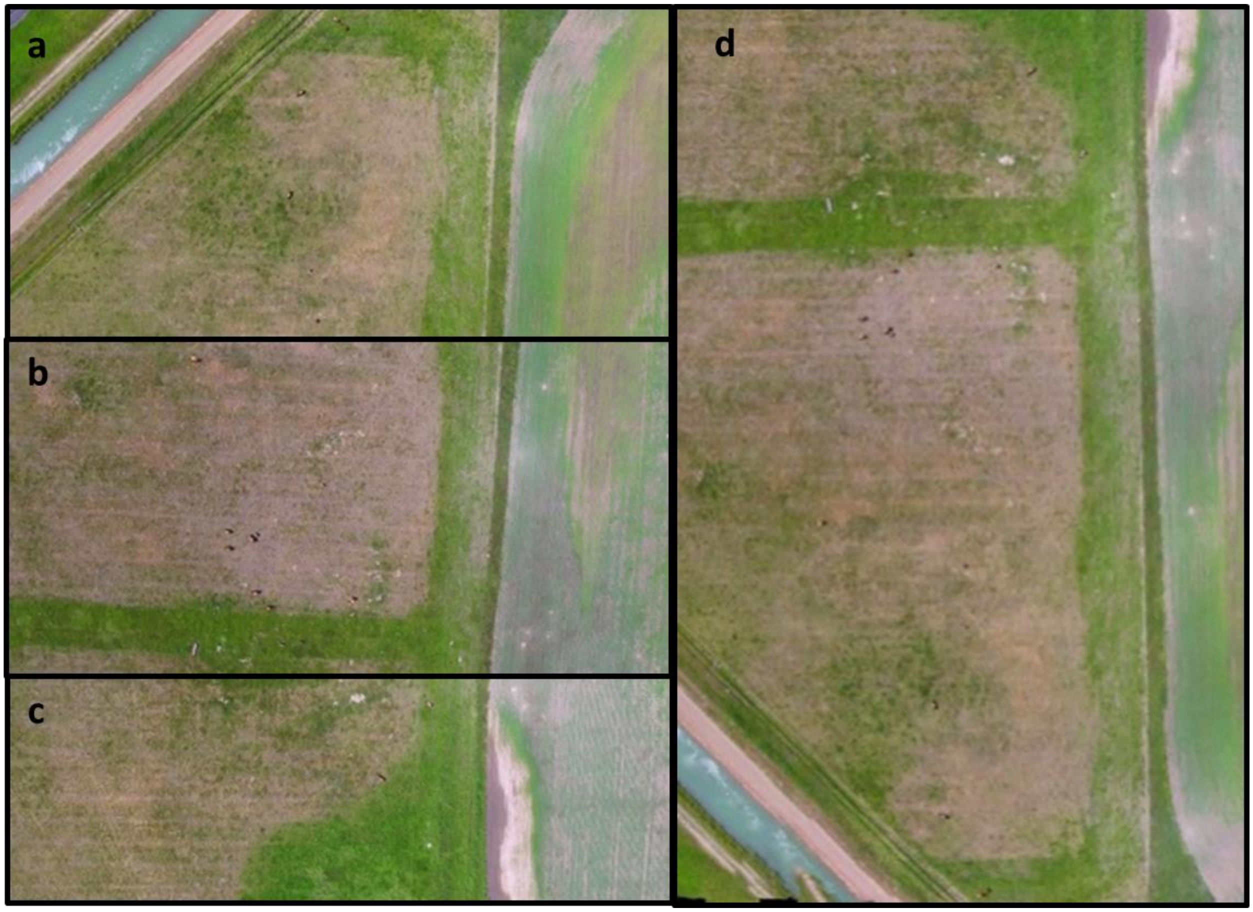

Figure 4a-d. Video screenshots of the cattle herd in the research pasture collected from a DJI Phantom 4 drone at an altitude of 100 m (a-c). Multiple photos of the herd were orthorectified together to make a single image (orthomosaic) of the entire herd (d).

Using image processing software (ImageJ), we measured the distance between calves and their mother cows (Calf-Dam group) and the distance between calves and non-related cows (Cow-Other group). The cow-calf distances can be quantified on the orthomosaic by measuring the number of pixels between two points. Using the ImageJ software, we marked the penning tag on the back of every individual in the orthomosaic image and obtained the x- and y-coordinates of each mark. These coordinates were used to geometrically determine the cow-calf distances. A pixel to meter ratio was obtained by calibrating the image with a known reference length to measure the cow-calf distances in meters. Thus, we measured the distance between every individual in the herd. The cattle in the research pasture aggregated in different areas of the pasture throughout the study, and we generated an orthomosaic image for each of the areas. Thus, we used different reference objects, one for each of the areas: a feeding trough that was 3.51 m in length, and the distance between two distinct fence posts, which were 42.6 m apart for one set of posts and 30 m for the other set of posts (Figure 5).

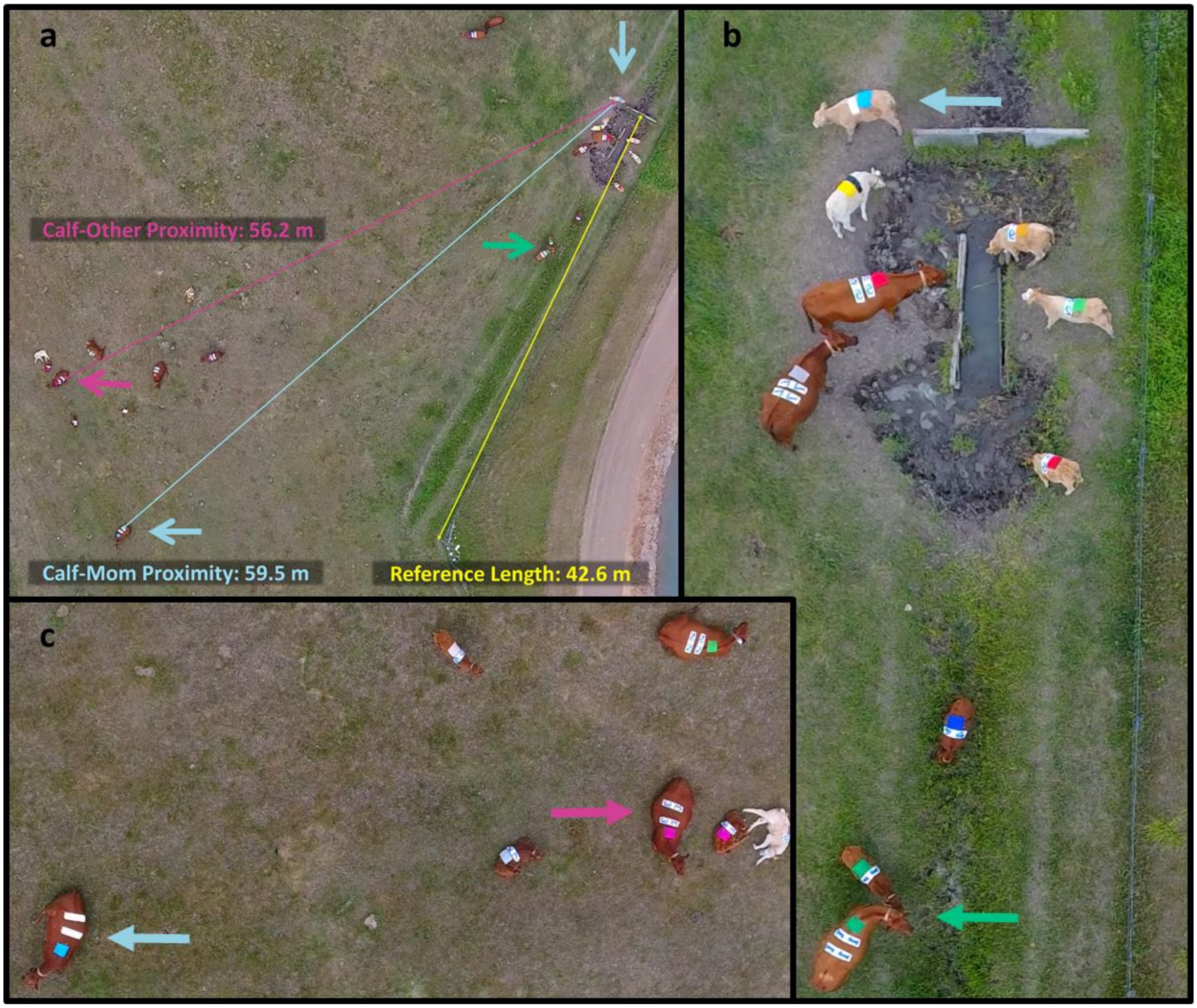

Figure 5. An example of an orthorectified image (orthomosaic) used to determine cow-calf distances (a). The number of pixels between the penning tag of a cow and a calf were measured using ImageJ. A reference length measured in the field was used to calibrate the image to obtain a pixel to meter ratio. Two photos obtained from taking a screenshot from the UAV flying at a height of 15 m are shown (b and c) around the orthomosaic (a). Photos screenshotted from the low-flying drone were used to identify each individual in the orthomosaic. The magenta, blue, and green arrows in photo "a" are matched with arrows in photos "b" and "c" to illustrate how the cattle in the orthomosaic are matched with the photos obtained from the low-flying drone.

Testing data reliability

We sought to determine if our measurements on ImageJ software were both accurate (i.e., were distances measured using the software close to the true distance measured in the field) and precise (i.e., were they consistent). To do this, we tested two orthomosaics in each of our six time periods, except for Day 2 Daytime, for which we had only one orthomosaic in this time period that contained the reference objects needed to make comparisons. This gave us a total sample of 11 orthomosaics to represent the error of our total data set of 76 orthomosaics. For each of the 11 orthomosaics, we calibrated the pixel to meter ratio using a reference object in the image that we measured in the field, then measured the length of a second reference object that was also measured in the field (Figure 6) to make measurement comparisons. These references were described earlier. This process was repeated three times for each orthomosaic (to test our consistency), giving a total of 33 comparisons to determine the difference between the length of a reference object measured using ImageJ software and the length of that object as measured in the field.

Figure 6. An orthomosaic used to test the accuracy of the distance measurements made on ImageJ software. In this example, reference 1 is a feeding trough used to calibrate the pixel to meter ratio on ImageJ and reference 2 is the distance between two distinct fence posts used to compare our software-measured length and the length measured in the field.

Statistical Tests

The cow-calf proximity could have been affected by the following variables: the day of study (days 1 - 4), the time period of the study (daytime or evening), and the relationship between the cow and the calf (whether the cow is the mother of the calf or the cow is unrelated to the calf). The cow-calf proximity significantly differed by day ($P < 0.001$), as an ANOVA. To remove the effect of day in further statistical analysis, the data were standardized by day such that the mean was equal to zero and the standard deviation was equal to one. The standardized data was used in a mixed model to examine the effect of time period, relationship, and the interaction between period and the relationship. We constructed the mixed model with the cow-calf distance as the response variable, time period and relationship as fixed effects and individual calf as a random effect. The mixed model was used as it accounts for pseudo replication (i.e., measurements were made on the same cows and calves at each sampling point) in our study. All tests were done using JMP 13 statistical software.

RESULTS

Time period had a significant effect on cow-calf proximity ($F_{1,849} = 101.79$, $P < .001$) as did cow-calf relationship ($F_{1,849} = 26.75$, $P < .001$). There was no statistically significant interaction between time period and cow-calf relationship ($F_{1,849} = 1.35$, $P = 0.245$). The mean cow-calf distance (n = 576) in the daytime was 39.8 ± 15 m (mean ± standard deviation) and in the evening (n = 288) was 84.3 ± 24 m (Figure 7). The mean proximity (n = 72) of the Calf-Dam group was 43.8 ± 24 m (mean ± standard deviation) and the mean proximity (n = 792) of the Calf-Other group was 55.6 ± 28 m (mean ± standard deviation).

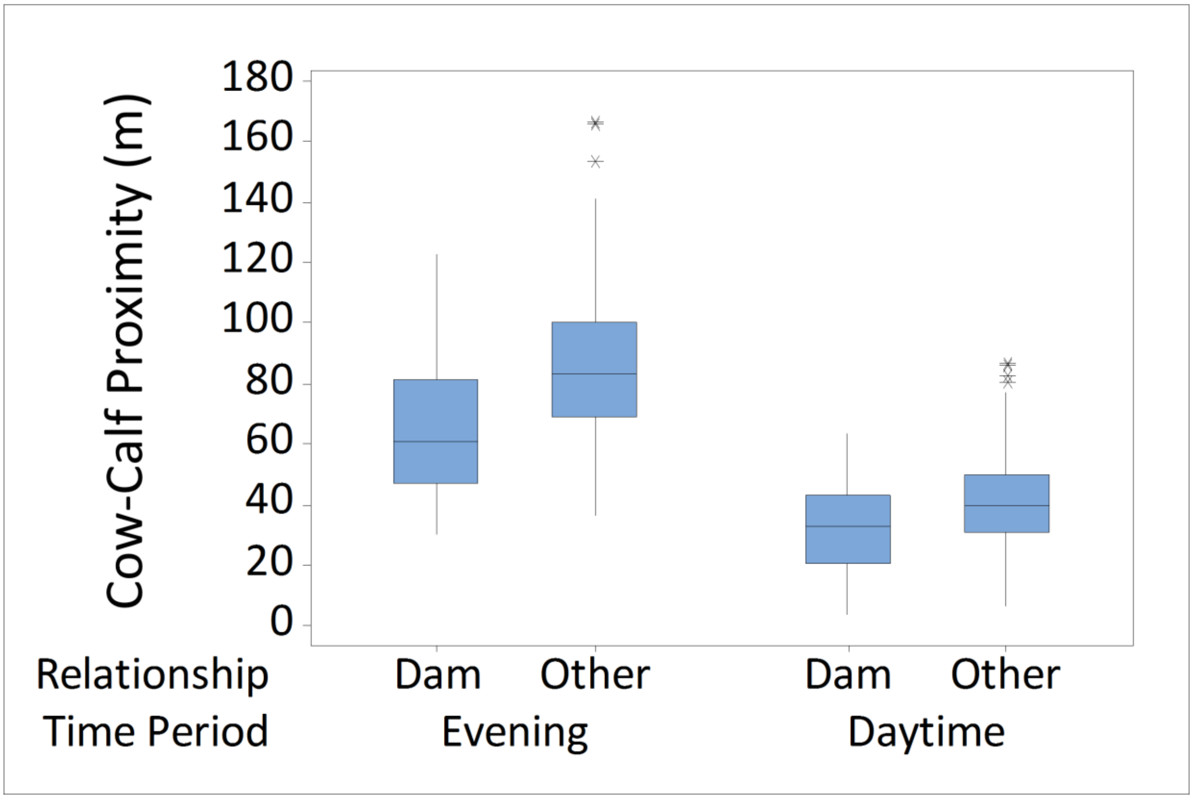

Figure 7. A box plot showing the distribution of cow-calf proximity by relationship and time period. Boxes indicate the interquartile range, lines across the boxes indicate the median, the whiskers indicate the upper and lower limits, and the asterisks indicate outliers.

At an individual level, the cow-calf distance ranged between 0.5 m to 304 m (Figure 8). The long tail of the distribution is skewed to the right, showing that the cow-calf distances substantially greater than the mean are less common.

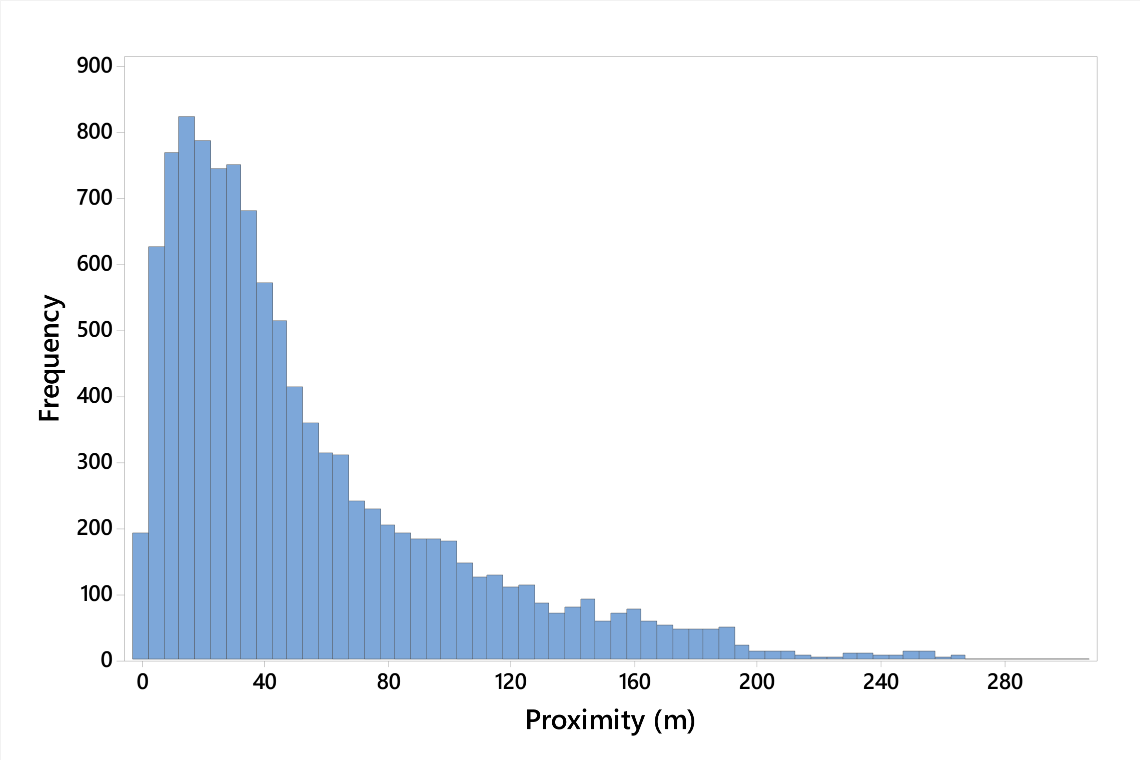

Figure 8. The distribution of cow-calf distances for individual pairs.

In the 11 orthomosaics that we used to test the accuracy and precision of our measurements, the mean difference between the measured length of a reference object and its true length measured in the field was 0.9 ± 0.7 m (mean and standard deviation). The maximum difference was 2.2 m. Within each orthomosaic, we measured the reference length three times and calculated the mean (n = 3); to test our precision, we calculated the standard deviation of each of the 11 means. The mean standard deviation within each orthomosaic (n = 11) was 0.2 ± 0.1 m (mean and standard deviation) and the max was 0.5 m.

DISCUSSION

Cow-Calf Affiliations

We examined the effects of time period and cow-calf relationship on cow-calf proximity. In both the evening and daytime periods, calves were closer to their dams than they were to other cows in the herd. This was expected since the calves require nursing from their dams. This is also consistent with observations made in previous cow-calf affiliation studies (Swain & Hurley 2007; Hirata et al. 2003).

All cow-calf pairs, regardless of their relationship (i.e., Calf-Dam or Calf-Other), were closer together in the daytime period than in the evening period, showing that the entire herd is more closely spaced in the daytime. The average cow-calf distance in the evening was twice as much as in the daytime. This strong diurnal variation in cow-calf distances may largely be attributed to the behaviour of the dams. Beef cattle exhibit a "hiding" predator-avoidance strategy in which dams leave their calves behind during maintenance activities (grazing, ruminating, and resting) and then return to the calf for nursing activities (grooming and milking) (von Keyserlingk & Weary 2007). Young animals generally reduce their activity to minimize predator risk in species that employ the "hiding" strategy (in contrast, in species employing a "following" strategy, the young stay closer to their mothers at all times) (Fisher et al. 2002; Carl & Robbins 1988). Indeed, cow-calf distances in beef cattle have been shown to be largest when the dams are grazing, resting and ruminating and lowest when the calves are nursing (Hirata et al. 2003). Video observation showed that the cows in this study spent a greater proportion of time grazing and walking in the evening periods than in the daytime periods; in the latter, they seemed to spend a greater proportion of time lying down. Since this study was carried out near the hottest time of the year in Lethbridge, AB, it may have been more comfortable for cattle to forage in the evening; especially since there was no shade in the research pasture. This may be a reasonable explanation for the strong diurnal variation in the cow-calf distance differences observed in this study.

Accuracy of Measurements

There are several sources of error that may have potentially affected the accuracy and precision of our distance measurements. Orthomosaics are generated by orthorectifying multiple photos together through a computational process using photogrammetry software. We used photos that were screenshots of video captured by camera-equipped drones flown at an altitude of 100 m above ground level. Because we manually flew the drones when recording video, the height at which the drone was flying during recording may have varied among our 76 sample points; however, this variation was likely no greater than two meters. Even though the camera is gimbal-stabilized, we experienced strong winds in the field location in Lethbridge, AB, which may have tilted the camera angle, and moved the drone to a slightly different altitude during the time a single video was made. This made it difficult to collect each video, and subsequently each screenshot, consistently in terms of angle and height. In addition, to make an orthomosaic of a given area, multiple overlapping photos of the same area are needed and it is optimal to have a consistent amount of overlap among the photos. However, for our orthomosaic images, we used screenshot images that were manually taken from a computer, so the degree of overlap among photos varied; this potentially affected the quality of the orthomosaic. Furthermore, the spacing of the cattle in the herd varied substantially among time points so each orthomosaic required a different number of photos to orthorectify between each 15-minute sampling time period. As a result of these factors, the resolution (i.e., pixel density) of each orthomosaic varied.

Orthomosaics are typically used to create composite images of still objects. However, many individual animals in our research herd were active when we took screenshots used for creating the orthomosaic. An active animal could be in different locations in overlapping photos of the whole cattle herd. As a result, some animals are distorted or stretched in our orthomosaic images of the cattle herds. This stretching and distortion made it difficult to tell where the penning tag was truly positioned on and animal's back, which would reduce the accuracy of our distance measurements. However, only a small number of individual animals appeared distorted and/or stretched appeared in our orthomosaics: In 19 of the orthomosaics, there was only 1 distorted animal, in 8 orthomosaics there were 2, and in 5 orthomosaics, 3 distorted animals appeared. In addition, the overall extent to which this affects the measurement accuracy is relatively small. Generally, a distortion or stretch would have caused us to mark the center of the penning tag up to an animal's length away from the true position of the center of the penning tag.

In rare cases (2 out of the 76 orthomosaics), the same animal would appear twice in the same image or an animal would be completely missing from the orthomosaic. This image distortion is an issue that has also affected other studies in which UAVs were used to capture photos for animal enumeration (Hodgson et al. 2016; Whitehead et al. 2014b); in these studies, photoshop was used to manually stitch together multiple photos into one composite image that captured every animal and as a result, some animals appeared distorted. However, in a recent study, Seymour *et al.* (2017) used a UAV to capture photos of grey seal (*Halichoerus grypus*) colonies and generated orthomosaics; the orthorectification of their images corrected for inconsistencies that could have resulted from animals moving in between photos. In our study, it is possible that the distorted animals weren't corrected by orthorectification either because our cattle moved too fast between photos or because there wasn't enough overlap in the photos used for orthorectification. Flying the UAV faster to take overlapping photos of the entire herd more quickly would likely reduce the number of distorted animals that appear in orthomosaics since there would be less time for animals to move between photos. Capturing photos at a higher frequency, for example, at sub-second intervals (Seymour et al. 2017), may also reduce the number of distorted animals that appear in orthomosaics since it would provide more data for computational software to calculate an average location of a moving animal.

Various types of human error may also have influenced results. These include manually measuring distances using ImageJ software. It is difficult to manually mark the exact spot of the cattle penning tag on each individual on every orthomosaic using the ImageJ software. It is equally difficult to mark the same spot on the fence posts and feeding troughs (i.e., our known reference lengths). This ultimately affects the precision of the distance measurements. However, we have demonstrated that the extent to which this affected the precision is small; in 11 different orthomosaics that we tested, our measurements were consistent to 0.5 m. In addition, the mean (n = 11) difference between the length of a reference object that we measured on ImageJ software and the length of that reference object that we measured in the field was 0.9 ± 0.7 m (mean ± standard deviation), which indicates that our distance measurements were accurate enough to make reliable inferences on fine-scale social interactions between animals. Thus, we are reasonably confident that our method to quantify cow-calf social interactions should allow us to make inferences about different facets of the social behaviour of cattle, especially interactions between cows and calves.

Future Use of UAVs in Studying Cattle Behaviour

Using unmanned aerial vehicles to quantify social affiliations has many benefits over traditional methods of direct observation. Consumer-grade and industry-grade UAVs are becoming increasingly more affordable, as the popularity and production rate of the vehicles has increased over the last decade. As a result, UAVs have been used for wildlife monitoring, ecological surveys, and a plethora of industrial applications (Ge et al. 2016; Przyborski et al. 2015; Cajzek & Klanšek 2014; Moranduzzo & Melgani 2014). UAVs are likely more cost-effective for quantifying social affiliations in cattle than use of traditional remote sensing technology and/or radio telemetry devices. Only one UAV is required to monitor a whole herd, as opposed to providing tracking devices for every single animal being studied. Furthermore, consumer-grade UAVs on the market today are likely more reliable given that collars equipped with GPS, GNSS, and radio transmitters typically require a high degree of expertise, have greater distance error, and have additional issues such as damage by weather, animals themselves and battery limitations. Lastly, using UAVs eliminates the potential risk of compromising animal welfare as they tend to be less invasive (reviewed by Christie et al. 2016). Collars represent extra weight for individual animals to carry, and may cause skin abrasions if they are not properly fitted. Though UAVs may initially appear to provide a strong visual and auditory stimulus, we observed that the cattle in our study rapidly habituated to the UAVs over a short period of time. During the habituation period of our study, we noticed that cattle were observant of the UAVs when they flew overhead at a proximity of 10 m. After a few days of habituation, the cattle showed no visually observable behavioural response to the UAVs at an altitude of 10 m. Many species of animals show little or no behavioural response to UAVs (reviewed by Christie et al. 2016), except in cases where the UAV is flown at close proximity (for example, see Ditmer *et al.* 2015) A recent study has also demonstrated that cattle (*Bos taurus*) do not seem to be disturbed by overhead UAVs (Mulero-Pazmany et al. 2015). These researchers did not visually observe any signs of response in free-ranging cattle when they surveyed at an altitude of 100 m. For domesticated cattle, no behavorial responses were reported by Whitehead *et al.* (2014b), who captured images of cattle in a feedlot at an altitude of 100m. Even at a closer altitude of 25 m, drones show no effect on the feeding behaviour of cattle between habituated and non-habituated groups (Nyamuryekung'e et al. 2016).

In conclusion, we successfully developed a novel and non-invasive method to quantify cow-calf social affiliations using unmanned aerial vehicles to take photos and then using photogrammetry to orthorectify multiple photos of the cattle herds from various offline video-screenshots collected by the UAVs. We have thus strongly supported our hypothesis that UAVs could be used to quantify social affiliations of beef cattle in a field setting. This method allows us to determine distances among all the individuals of the herd with a sufficient level of accuracy and precision to provide meaningful data to study social behaviour in cattle. In future work, this method could help advance our understanding of the organization of social groups and hierarchies within a herd, which are formed to reduce aggressive behaviour among individuals and maintain group cohesion (Mendl & Held 2001). In addition, this method allowed for capturing high-quality video aerially and at a very close distance, which would be useful for observing other important cattle behaviours, such as ruminating and nursing. Studying these behaviours in cattle is important for increasing our understanding of animal welfare (de Oliveira et al. 2014) and would ultimately be beneficial for managers in the beef cattle industry who are trying to develop better management practices. Using UAVs to further our understanding of cattle social dynamics could facilitate decisions that would optimize animal grouping, breeding, and maternal behaviour and/or grazing, any or all of which could potentially increase overall cattle productivity on farms.

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