Hornography: Photogrammetry and 2D Measurement Can Be Used to Assess Bighorn Sheep (*Ovis canadensis*) Horn Morphology

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ABSTRACT: As a result of a review of arguments addressing the selection and counterselection of secondary sexually selected traits in Rocky Mountain bighorn sheep (*Ovis canadensis*). We have identified some gaps in our knowledge which complicate our ability to study and comment on the matter. The primary issue is that horn measurements are routinely completed for deceased bighorn sheep; either individuals that have been legally hunted, found dead or confiscated. Additionally, measurements are done at time of capture, which tends to occur during the first few years of life. Thus, data sets compiled using this approach are inherently biased towards larger males, as those are the ones that are targeted later in life. Therefore, as not all sheep are found dead, the measurements based on deceased individuals and juveniles do not necessarily represent the living population. Given, the bias in existing datasets, we decided to investigate whether the size and annual growth of bighorn ram horns could be accurately measured using non-invasive photographic techniques, specifically using photogrammetry and 2D measurements on photographs from live animals. Our second goal was to use photogrammetry to build 3D models that could provide scaled depictions of a male's horn size and shape. To test the accuracy of the 2D measurement technique, we used photos of sheep with known manual measurements and compared the digital and manual measurements. To test the accuracy of the photogrammetry technique, we used the method on the horn of a deceased individual. A scaled 3D model was produced with annuli, scars, and breakage clearly visible. Therefore, it is reasonable to expect that photographs and subsequent photogrammetry analyses will provide a reliable, non-invasive approach to studying the variation in horn morphology amongst living bighorn sheep rams.

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INTRODUCTION

Sexually selected traits such as weaponry, bright colours, and body size are often correlated with an individual male's fitness (Darwin 1871, Fisher 1915). However, very often studies of these traits are done on captive or diseased individuals if they are not regularly caught and measured. While exploring different ways to measure secondary sexually selected traits in bighorn sheep (*Ovis canadensis*), such as horns, we identified some issues with these measurements in that they are routinely completed for deceased bighorn rams, either individuals that have been legally hunted under minimum harvest size regimes, were found dead or were confiscated. Additionally, for monitored populations, measurements are done at the time of capture, which tends to occur during the first few years of an individual's life. Thus, the data sets compiled by this approach are inherently biased towards larger males, as those are the ones that are targeted by trophy hunting (Festa-Bianchet *et al*. 2015, Festa-Bianchet 2017, Pelletier *et al*. 2012). Therefore, the measurements of deceased individuals are not necessarily representative of all males in a population which complicates the assessment of the impact of hunting, environmental pressures, demographic pressure and disease on horn growth (Festa-Bianchet and Mysterud 2018).

Male Rocky Mountain bighorn sheep are an ideal study organism as their exclusive trophy harvest is closely monitored, making manual growth measurements available for study through the government agencies and long-term projects. Additionally, annuli allow for age determination (Geist 1966) and digital measurement of annual growth. Furthermore, large horn size is correlated with a higher rank in the mating hierarchy (Geist 1971). As there is a high mating skew for bighorn sheep rams, the tending or high-ranking males enjoy higher reproductive success than subordinate males (Geist 1971, Hogg and Forbes 1997). Lastly, horn size is a heritable trait with a reported h^2-value of 0.397 (Pigeon *et al*. 2016). Therefore, the systemic removal of dominant rams, with rapid horn growth rates, has the potential to drastically alter the age structure of the population (Schindler *et al*. 2017) and the reproductive success of the survivors which could, over time, cause a decline in horn size (Coltman *et al*. 2003, Pigeon *et al*. 2016, Schindler *et al*. 2020).

Previous work on Ibex (*Capra ibex*) has shown that total and annual horn growth can be reliably measured using photographic techniques (Bergeron 2007, Willisch *et al*. 2013). However, ibex have relatively straight horns in comparison to those of bighorn sheep. To our knowledge, photographic measuring techniques have not been tested and calibrated for animals with curled horns. Thus, given, the bias in existing datasets, we decided to investigate whether the size and annual growth of bighorn ram weaponry (horns) could be accurately measured using non-invasive photographic techniques, specifically using photogrammetry and 2D measurements on photographs from live animals. Our second goal was to use photogrammetry to build 3D models that could provide scaled depictions of a male's horn size and shape. If these models are accurate, then more detailed measurements could be taken and dimensions calculated (i.e., the volume of yearly horn growth, entire horn volume). In this paper, we discuss the 2D measurement techniques and the development of 3D models, comparing them to manual measurements. Our study shows that these techniques reflect manual measurements of live or dead animals very closely and propose that these be considered in lieu of captures or working on dead animals exclusively.

METHODS

Study Organism and the Long-term Database

The bighorn sheep population at Sheep River Provincial Park (SRPP), Alberta, Canada, is part of a long-term study and therefore a long-term photographic data set (compiled by Dr. Kathreen Ruckstuhl and her collaborators since 2006) is available. As part of the long-term monitoring project, the bighorn sheep are captured primarily as lambs. During capture, DNA is collected, and the individual is fitted with ear tags that correspond to a unique identification number (Ruckstuhl 1998). Therefore, over 90% of the sheep are individually identifiable through ear tags, which enables tracking them throughout their lives.

STUDY AREA

This study was conducted in Sheep River Provincial Park located in Kananaskis, Alberta, Canada (50º38'55" N 114º37'38" W) from the University of Calgary's R.B. Miller Field Station. The region is located on the eastern slopes of the Rocky Mountains and is dominated by grasslands, pine, and aspen forests as well as a river canyon and open meadows.

Photographic Techniques

The first photographic technique we explored was 2D digital measurement of annual growth. Photos of rams, with known scales (Fig. 1.) were loaded into ImageJ (Abramoff *et al*. 2004, Rasband 2018) allowing for the measurement of annual growth. Two methods of including known scales in the photographs were calibrated. 1) Photos were taken with parallel laser points projected onto the ram's horn spaced 4 cm apart (laser setup method adapted from Bergeron, 2007). 2) The ear tags are a standard shape and size and therefore their height (3.7cm) can also be used as a known scale. We recommend using the height of the ear tag as opposed to the width as the width can be distorted in images due to the position of the ram's ears within a 2D plane. However, the height of the ear tags does not change regardless of ear position. Digital measurements were compared to corresponding manual measurements taken post-mortem and/or during capture using linear regressions that were forced through the origin. Our sample size was 65 annuli from nine rams aged two to ten years old.

The second photographic technique we explored was photogrammetry. We mounted the horn of a deceased eight-and-half-year-old ram onto a rotating pedestal. Using a tripod, 200 photos were taken while rotating the horn roughly 1 cm between shots; photos were taken with the camera positioned beneath, level with, and above the horn. Using the software AgiSoft Metashape Professional (2020), these photos were aligned using 200,000 points to create a point cloud (Fig.2. Left) A mesh was then applied to connect the points and eliminate outlying points thereby creating a solid computer model (Fig. 2. Middle). Finally, the model was textured which involves adding fine details and colour to the exterior layer (Fig. 2. Right). The final model was then 3D printed. Both the virtual and physical model were visually compared to the real horn.

RESULTS

2D Measurement

The comparison between digital measurements done in ImageJ (Rasband 2018) and the manual measurements was a close match (Fig. 3 and 4). Overall, the digital measurements were accurate to within 5mm of the manual measurements.

Photogrammetry Generated 3D Model

Using photogrammetry, we produced a 3D print of a horn from an eight-and-a-half-year-old deceased ram. Through visual comparison of both the digital and physical 3D model, we determined it to be an accurate representation of the actual horn (Fig. 5). The annuli and markings on the horn were clearly visible and the spread mirrored that of the real horn (Fig. 5). Thus, 3D models could be used as a non-invasive tool to determine annual growth patterns for living individuals and growth increments could be measured either by the length and circumference of the annuli, or the volume of growth be further calculated.

DISCUSSION

Using 2D photo analysis and photogrammetry, we have demonstrated that the size, shape, and breakage of bighorn ram horns can be evaluated while the individual is alive without necessitating capture. This allows researchers to assess the weaponry size of living individuals non-invasively. Some limitations must be taken into consideration though. For 2D digital measurement of annual growth to be successful, numerous profile and head-on photos are needed where the individual of interest is the main subject in the photo. If the bighorn sheep are marked, ear tags provide a reliable, known scale as ear tag dimensions are standardized. Alternatively, we have shown that for unmarked rams using parallel laser pointers and a camera, very precise measurements can be taken from live animals in the field. Furthermore, if using ear tags and/or laser pointers as known scales is not feasible (i.e., studying unmarked animals from a distance

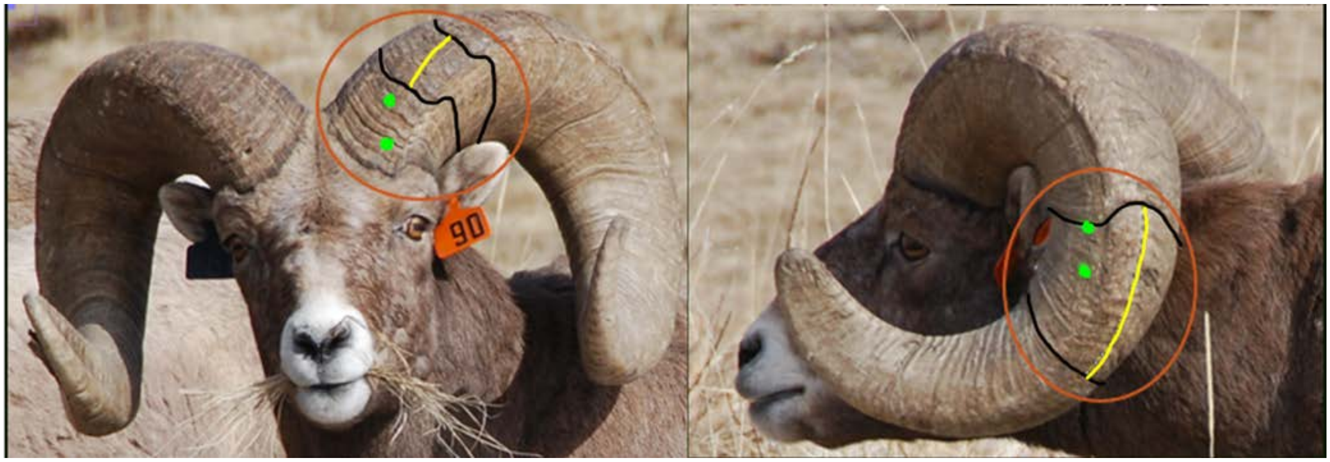

Figure 1. A photographic example of a digital 2D measurement of the annual horn growths of a bighorn ram (ram ID=706). Annuli (grooves where horn growth was arrested during winter) are indicated in black. Laser points are the green-filled dots, representing 4 cm between them (centre to centre). The yellow line shows the measurement for one year's (annual) growth. Note the ear tag height (3.7 cm) can be used as a known scale. Photo credit: K. E. Ruckstuhl.

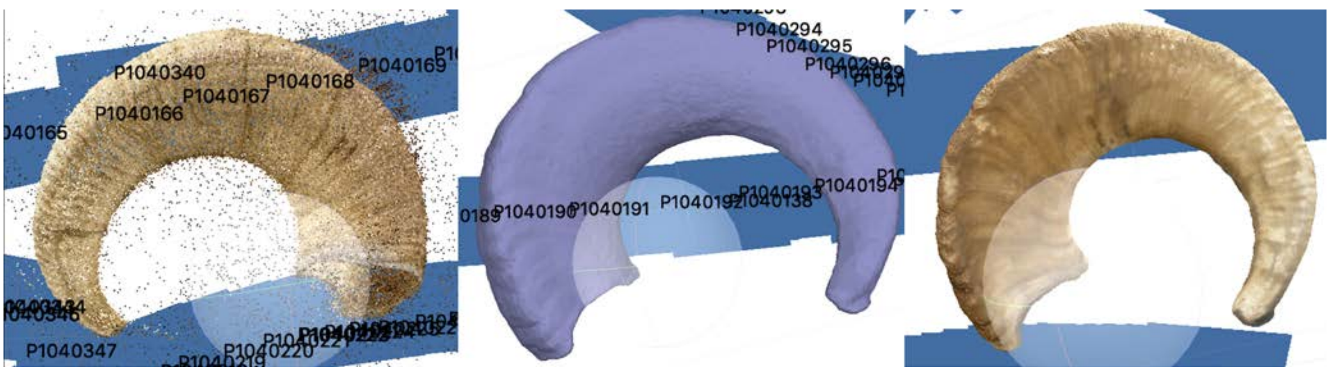

Figure 2. The stages of creating a digital 3D model of an eight-and-a-half-year-old ram's horn in Agisoft Metashape Professional (2020). On the left is the point cloud model. In the middle is the mesh model. On the right is the final, textured computer model. Blue squares and associated writing correspond to the position of individual photographs. Model/ photos by T.C. Henry.

greater than ~50m) scaling objects in the vicinity (such as trees, rocks, road markers or rams with known horn measurements) may provide an accurate alternative (Willisch *et al*. 2013) so long as the scaling object and the ram of interest are photographed in the same plane.

Although, we were successful in creating a digital 3D model and a print from a deceased individual, photos were taken in the lab, with known angles. Thus, the challenge will now be to evaluate how many pictures need to be taken of a living ram to be able to create precise 3D models. Our recommendation is to take pictures of individuals while they are standing or bedded, and enough photos can be taken from different angles, while they are relatively sedentary.

Overall, we believe that non-invasive photographic techniques provide a promising method of assessing the horn size of live individuals without the need for repeated captures, thus facilitating future studies on the evolution, growth and use of sexually selected weaponry. This would allow researchers to obtain data that is more representative of the entire population and

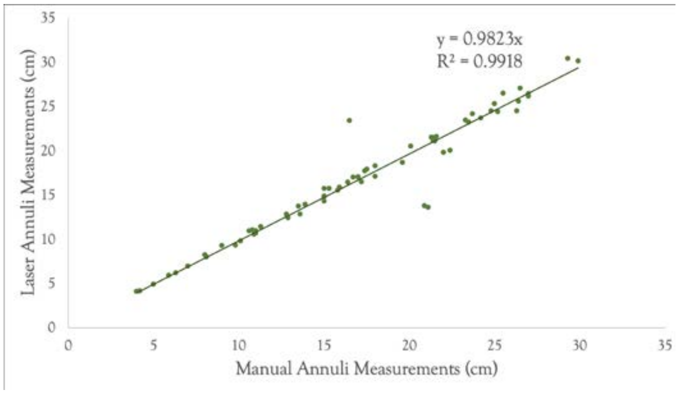

Figure 3. Comparison of manual and digital measurements (cm) of annual growth. The digital measurements were taken using photographs of rams with parallel lasers spaced 4 cm apart projected onto the rams' horns as a known scale. The sample size is 65 annuli from nine rams aged two to ten years of age. Note, the linear regression was forced through the origin.

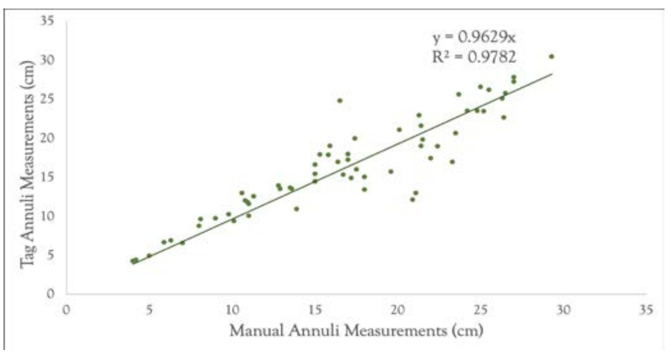

Figure 4. Comparison of manual and digital measurements (cm) of annual growth. The digital measurements were taken using photographs of rams with the height of ear tags (3.7 cm) as a known scale. The sample size is 65 annuli from nine rams aged two to ten years of age. Note, the linear regression was forced through the origin.

Figure 5. Visual comparison of a photograph of a horn from a deceased eight and half year-old ram to the 3D printed model of the horn. Note the visibility of the annuli, breakage, and shape. Model and photo by T.C. Henry.

not biased towards deceased larger males who are almost exclusively hunted for sport. Once this method is standardized, it can be applied to any size and shape of sexually selected traits.

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