

USE OF TRAIL CAMERAS TO ESTIMATE THE ABUNDANCE AND POPULATION STRUCTURE OF BIGHORN SHEEP IN BAJA CALIFORNIA, MEXICO

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ABSTRACT

Monitoring abundance and population structure is essential to guide the management of wild species. Few population studies of bighorn sheep (*Ovis canadensis* Shaw) have been conducted in Baja California, Mexico, due to the complicated and costly nature of monitoring these animals. The objective of the study was to determine the abundance and structure of a bighorn sheep population using trail cameras. The study was conducted in the coastal region of the Sierra Santa Isabel from April to July 2022. Trail cameras were deployed at four natural watering holes and on a trail that is frequently used by bighorn sheep. The Lincoln-Petersen method was used to estimate abundance with four criteria to define independent records: separated by one hour, by one hour without taking into account samples with only one record, by at least one day, and by one week. The estimates generated with this method were compared with those reported in the aerial monitoring conducted in the study area in 2021. The abundance calculated from independent sampling periods separated by one week was found to be within the range of that estimated from aerial monitoring. The abundance of bighorn sheep in the coastal region of the Sierra Santa Isabel was 129 ± 9 animals, and the ratio of rams, ewes, yearlings, and lambs was 8:10:1:2. The results suggest that the population of the species at this site is in a good state of conservation. In addition, the use of trail cameras proved to be a viable alternative to traditional monitoring methods for bighorn sheep population assessments.

Key words: wild sheep, big game species, population status, Lincoln-Petersen, *Ovis canadensis* Shaw, Sierra Santa Isabel.

INTRODUCTION

Population monitoring is the fundamental mechanism for collecting biological information and systematic data needed to determine the conservation status and demographic trends of wildlife populations (Bolen and Robinson, 2003). In addition, it allows the evaluation of the impact of the factors that exert pressure on these populations, as well as the effectiveness of the conservation actions applied for their protection (Kuvlensky *et al.*, 2022). Among the essential attributes to guide the management of wild species, the abundance (expressed in the number of individuals) and demographic structure (encompassing sex ratio and age classes) of these populations stand out (Gallina-Tessaro, 2015).

Bighorn sheep (*Ovis canadensis* Shaw) play an ecological role in the desert scrublands of northwestern Mexico, as they are directly involved in the nutrient cycling of the ecosystem (Monson and Sumner, 1980), influencing vegetation dynamics (Gastelum-Mendoza *et al.*, 2024), and being a source of nourishment for some predators (Rosas-Rosas *et al.*, 2003). They also possess cultural (Sandoval *et al.*, 2019) and economic importance (Lee, 2011). In Mexico, it is classified as a species subject to special protection (SEMARNAT, 2019), which implies that its exploitation must be based on accurate information on the status of its populations to avoid jeopardizing its viability. Therefore, it is imperative to have efficient monitoring methods that provide useful data on the abundance and structure of these populations (Ruiz-Mondragón *et al.*, 2023).

This species inhabits arid mountain systems with steep slopes and difficult access (Conroy *et al.*, 2018), where monitoring its populations demands a considerable investment of time, money, and technical personnel. Among the methods used to determine their abundance and population structure are aerial monitoring (Romero-Figueroa *et al.*, 2024), ground monitoring (López *et al.*, 1995), and trail camera monitoring, the latter being a lower-cost and less intrusive methodology that allows for periodic and standardized population estimates (Perry *et al.*, 2010; Harris *et al.*, 2020).

In this regard, several methods based on the use of trail cameras have been developed to estimate the abundance of wild species, both for populations with marked specimens (Alonso *et al.*, 2015) and populations with no marked specimens (Palencia *et al.*, 2021). For bighorn sheep, accurate estimates of population size have been obtained using trail cameras under captive conditions (Perry *et al.*, 2010; Harris *et al.*, 2020). However, for free-living sheep populations, the most viable alternative for estimating abundance is the Lincoln-Petersen mark-recapture method (Jaeger *et al.*, 1991; Douglass and Longshore, 1995). Methods developed for unmarked populations require cameras to be randomly placed in the delimited study area (Palencia *et al.*, 2021), which increases sampling costs due to the inaccessible and rugged habitat of this species.

When using the Lincoln-Petersen method for population estimation, the assumption is to work with a closed population where all animals have the same probability of being captured, remain tagged throughout the sampling period, and observers may

detect all tags (Pollock *et al.*, 1990; Perry *et al.*, 2010). Therefore, a catch period is set to fit the limitations of the method; in addition, to mitigate the risk of violating the assumptions of the method, a cumulative estimate should be made from a sufficient number of individual catch periods (Jaeger *et al.*, 1991; Douglass and Longshore, 1995; Perry *et al.*, 2010).

In the state of Baja California, Mexico, the evaluation of the size and structure of bighorn sheep populations has been scarcely addressed, which is reflected in the existence of only five aerial monitoring studies (Romero-Figueroa *et al.*, 2024) and one terrestrial monitoring study (López *et al.*, 1995). This limitation in research is attributed to the lack of financial resources and trained personnel to sustain a continuous monitoring program for bighorn sheep populations, aggravated by the ban on sport hunting in Baja California since 1990 (Ruiz-Mondragón *et al.*, 2023). The lack of data has hindered the formulation of management plans that promote the conservation of both the species and its habitats in the Baja California region (Romero-Figueroa *et al.*, 2024).

In this context, it is important to have a method for monitoring bighorn sheep populations that is inexpensive and simple to implement, accessible to landowners, authorities, technical personnel, and researchers with a basic level of training and technological equipment. Therefore, this study aims to resolve the following questions: 1) What independent sampling interval produces a bighorn sheep population estimate comparable to that obtained from aerial monitoring? and 2) What level of sampling effort is required with trail cameras to achieve an estimate of bighorn sheep population abundance comparable to that from aerial monitoring? Therefore, the main objective of this research was to determine the abundance and structure of a bighorn sheep population in the wild using trail cameras as a monitoring method.

MATERIALS AND METHODS

Description of the study area

The study was conducted in the coastal region of the Sierra Santa Isabel, located in the central portion of the state of Baja California, Mexico (30.1544° N, 114.8464° W and 29.7933° N, 114.5209° W) (Figure 1). This area comprises a low mountain range with plateaus and covers an area of 43 888 ha, with altitudes ranging from 5 to 876 m. The climate is very arid and semi-warm, with an average annual temperature that varies between 18 and 22 °C. Rainfall is distributed throughout the year, with a percentage of winter rainfall greater than 18 % of the annual total ($BWh(x')$; García, 2004). Average annual precipitation ranges from 0 to 125 mm (Vidal, 1990). In terms of vegetation, microphyllous desert scrub predominates, with species such as the gobernadora (*Larrea tridentata*), ocotillo (*Fouquieria splendens*), and flor de rocío (*Encelia farinose*) (Miranda and Hernández, 1963).



Figure 1. Location of trail camera monitoring sites (red dots) in the coastal region of Sierra Santa Isabel, Baja California, Mexico.

The natural waterholes used by bighorn sheep are known locally as Tinaja del Miramar, Cinco Islas, La O, and Las Palmitas (Ruiz-Mondragón *et al.*, 2023). The longest distance between waterholes is 9 km and corresponds to the stretch between Tinaja del Miramar and Las Palmitas; the shortest distance between these water sources is 1 km and corresponds to the separation between Cinco Islas and La O. The Tinaja del Miramar is a waterhole that is 7 m wide, 4 m long, and 1 m deep. Cinco Islas is a body of water that springs in the bed of a stream; it is 1 m wide, 0.7 m long, and 0.3 m deep. The O is a cavern in the mountains; the body of water at this site is 1 m wide, 1.5 m long, and 0.3 m deep. Las Palmitas is an oasis immersed in the mountain range; the body of water at this site is 1.5 m wide, 2.5 m long, and 0.4 m deep (Figure 2).

The study was conducted from April 15 to July 31, 2022, which corresponds to the hottest season of the year in the region (García, 2004). However, the research was interrupted in July due to the passage of Hurricane Kay, which resulted in the loss of all cameras used in the study. Bushnell Core Low Glow 24 MP cameras were used to carry out the population monitoring. These cameras were installed at four natural waterholes and on a trail that is frequently used by wild sheep (Figure 1). A camera was installed at each site and mounted on a wooden stake at a height of 0.5 m from the ground and programmed to capture three photographs at 3 s intervals for each detection of motion. Monthly maintenance was performed to change memory cards and batteries.

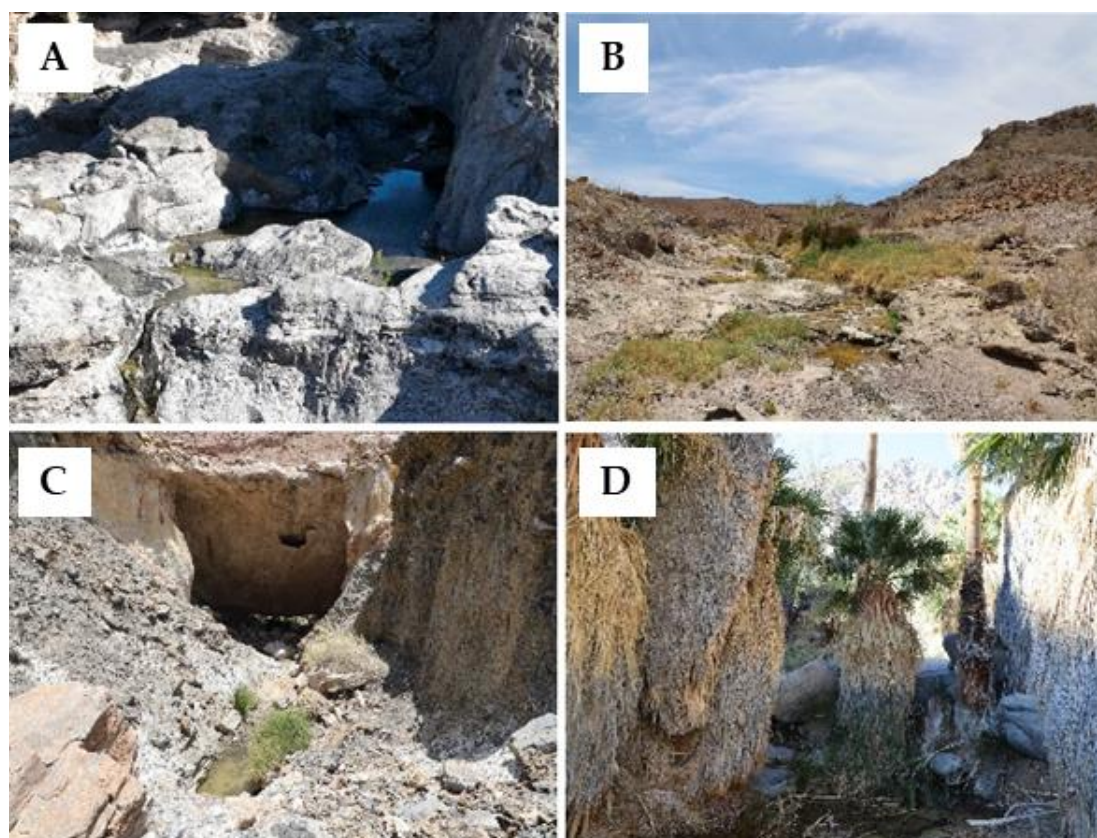


Figure 2. Natural waterholes used by bighorn sheep (*Ovis canadensis* Shaw) in the coastal region of the Sierra Santa Isabel, Baja California, Mexico. A: Tinaja del Miramar; B: Cinco Islas; C: La O; D: Las Palmitas.

For individual identification of the sheep, the natural characteristics of the animals were used, including the size and shape of the horns, body size, and condition, as well as scars, deformities, and other notable marks on the horns and body. Only records that could be fully identified were considered in the estimation of population size. All photographs of animals that could not be observed in sufficient detail due to poor lighting conditions, distance, or the speed at which they moved through the camera's field of view were excluded.

The use of natural characteristics to differentiate individuals in a population is not recommended in mark-recapture studies, as these characteristics may change over time, which could affect the accuracy of the estimate of population abundance. However, Perry *et al.* (2010) carried out a comparison of the estimation of the size of a bighorn sheep population considering different types of tags and found similar results.

The population size was estimated with the Lincoln-Petersen method (Chapman, 1951) modified by Pollock *et al.* (1990) according to the following formula:

$$N = \left[\frac{(n_1 + 1)(n_2 + 1)}{m + 1} \right] - 1$$

where N is the population size, n_1 is the number of individuals recorded (captured) and identified (marked) in the first sampling period, n_2 is the number of individuals recorded in the subsequent sampling period, and m is the number of individuals recorded in the first sampling period and recorded again in the subsequent sampling period (recaptured). The population size estimate was the average of all individual estimates. The 95 % confidence interval (CI) of the estimate was calculated as 1.96 times the standard error of the mean:

$$SE = \sqrt{\left[\left(\frac{1}{(k)(k-1)} \right) \left(\sum (N_i - N_m)^2 \right) \right]}$$

where K is the number of individual estimates of the population size, N_i is each individual estimate and N_m is the average estimate.

Four estimates of population abundance were made, each based on a different time period for independent sampling. To carry out these estimates, series of photographs separated by more than one hour, by at least one day, and by one week were considered as independent samples. Furthermore, an additional estimation was performed with independent samples separated by more than one hour, excluding those samples with only one record ($n_i = 1$) (Perry *et al.*, 2010).

In the case of independent samples separated by more than one hour, each set of photographs was considered as an individual sample. For example, if in the first photograph, two rams and one ewe were recorded, and in the second photograph, taken 45 minutes later, two ewes and one lamb were recorded, neither would equal six individuals: two rams, three ewes, and one lamb. For independent samples separated by at least one day, animals were recorded on the first day (n_1) and the following day on which the camera was activated (n_2). For example, if two sheep were recorded on April 15 and five on April 17, n_1 would equal two and n_2 would equal five. In the case of samples separated by one week, n_1 would be equal to the number of sheep recorded during the first seven days, and n_2 would be equal to the number of sheep recorded during the following seven days.

The cumulative average of the individual estimates of the population size (from $K=2$) was calculated. The precision of these estimates was evaluated by comparing them with the estimate reported for the study area in the 2021 aerial monitoring (Romero-Figueroa *et al.*, 2024). The success of trail camera sampling was estimated for each month and installation site, defining success as the number of independent samples obtained divided by the number of days/cameras used (one day/camera = one camera in operation per 24 h) (Perry *et al.*, 2010).

The bighorn sheep recorded were classified according to the age and sex class criteria defined by Geist (1968), labeling the sheep into eight categories according to the shape and size of their horns, as well as their body size (Figure 3). From this classification, the ram:ewe:yearling:lamb ratio of each individual estimate was determined. The age and sex class ratio for the estimated population was obtained as the average of all individual estimates. The Kruskal-Wallis nonparametric statistical test was used to compare the ratio of age and sex classes obtained from the different sampling periods. This statistical analysis was performed using the Past4 software (Hammer *et al.*, 2001). Likewise, the photographic records of the species were classified based on the social configurations observed: solitary, in pairs, or in herds.

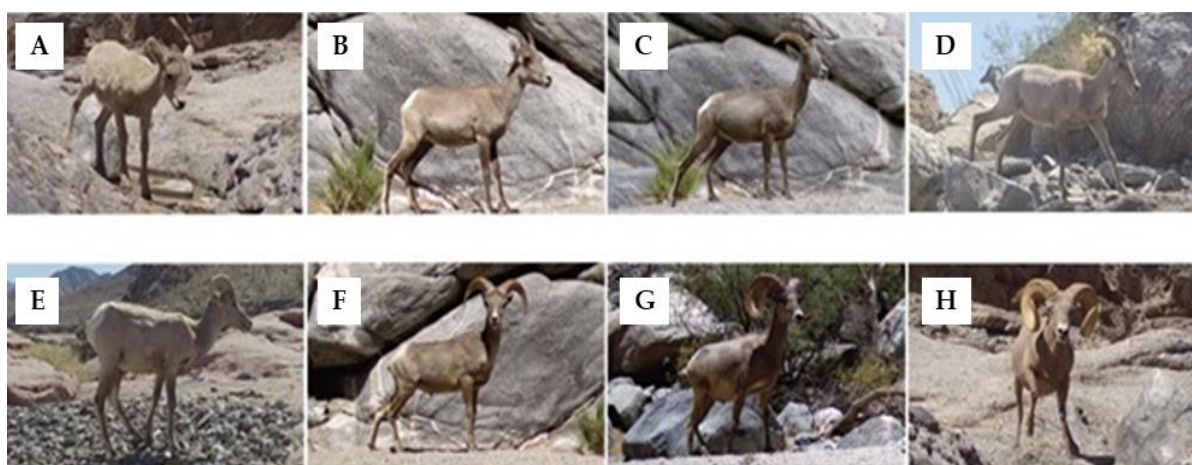


Figure 3. Age and sex classes of bighorn sheep (*Ovis canadensis* Shaw) according to Geist (1968). A: lamb; B: yearling ewe; C: ewe; D: yearling ram; E: class I ram; F: class II ram; G: class III ram; H: class IV ram.

RESULTS AND DISCUSSION

In 535 days/cameras, 6062 photographs of bighorn sheep were obtained. In 41 % (2468) of these images, the specimens could be fully identified. These records were organized into 255 independent samples, which consisted of series of photographs separated by more than one hour. In addition, 166 independent samples separated by more than one hour were obtained, each with more than one sheep per record, 99 independent samples separated by at least one day, and 14 independent samples separated by one week.

At each location where a trail camera was installed, photographs of the sheep were captured throughout each month during the study period (Figure 4). The number of images taken per day gradually increased over time, and there was no difference between the number of photographs taken at the different sites in April and May; however, in June and July, the number of images captured both on the trail and at Cinco Islas was lower than those obtained at La Tinaja del Miramar, Las Palmitas, and La O.

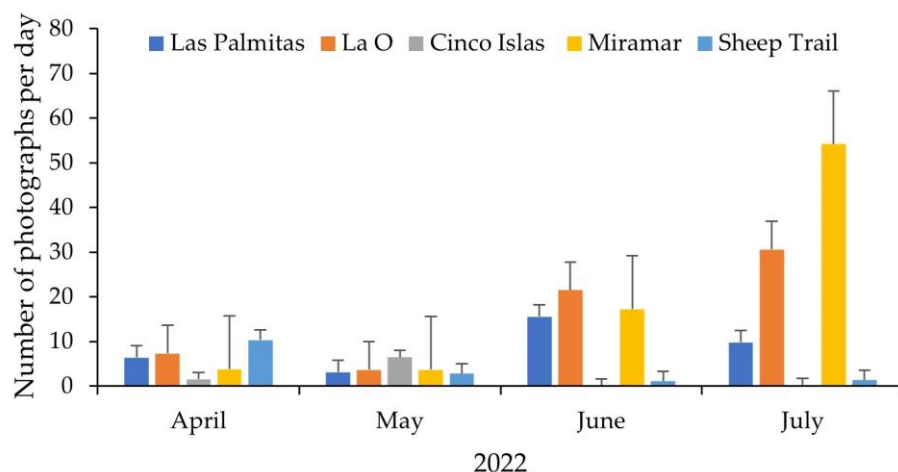


Figure 4. Trail camera photography rate according to month and monitoring site in Sierra Santa Isabel, Baja California, Mexico (vertical lines above bars indicate standard error).

With independent samples separated by more than one hour, 127 individual estimates of bighorn sheep population abundance were made. Likewise, 83 individual estimations were carried out with the independent samples separated by more than one hour and with more than one sheep per record, 49 individual estimations with the independent samples separated by at least one day, and 7 individual estimations with the independent samples separated by one week (Figure 5).

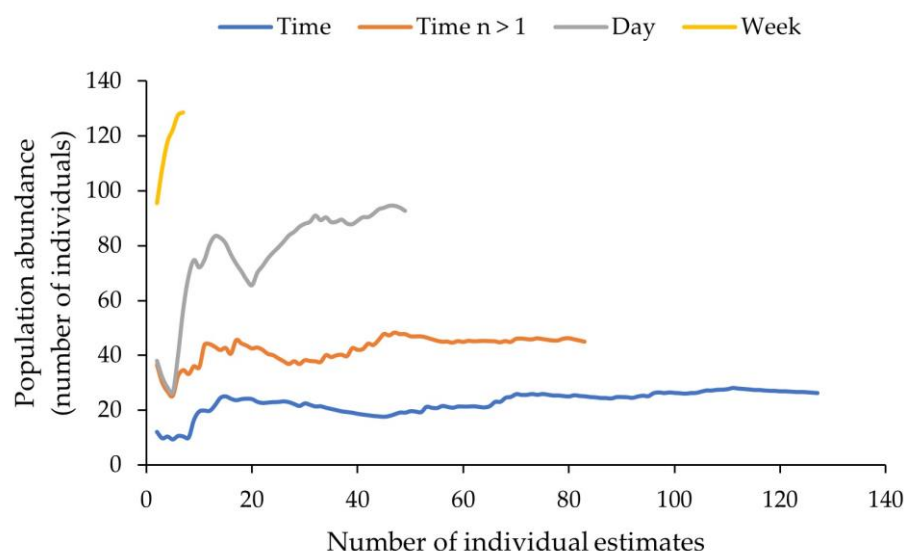


Figure 5. Average cumulative estimate of bighorn sheep (*Ovis canadensis* Shaw) population abundance for the coastal region of the Sierra Santa Isabel in Baja California, Mexico, based on different independent sampling intervals.

The maximum number of bighorn sheep recorded in a period of independent sampling separated by more than one hour, as well as in a period of independent sampling separated by more than one hour and with more than one sheep per record, was 56 different individuals; in a period of independent sampling separated by at least one day, it was 58 different individuals; and in a period of independent sampling separated by one week, it was 128 different individuals. The mean abundance of the species, together with its 95 % confidence interval, calculated from independent samples separated by more than one hour, was 26 ± 4 ($K = 127$); while from independent samples separated by more than one hour and with more than one sheep per record, it was 45 ± 4 ($K = 83$); 93 ± 7 ($K = 49$) with independent samples separated by at least one day; and 129 ± 9 ($K = 7$) with independent samples separated by one week (Figure 6).

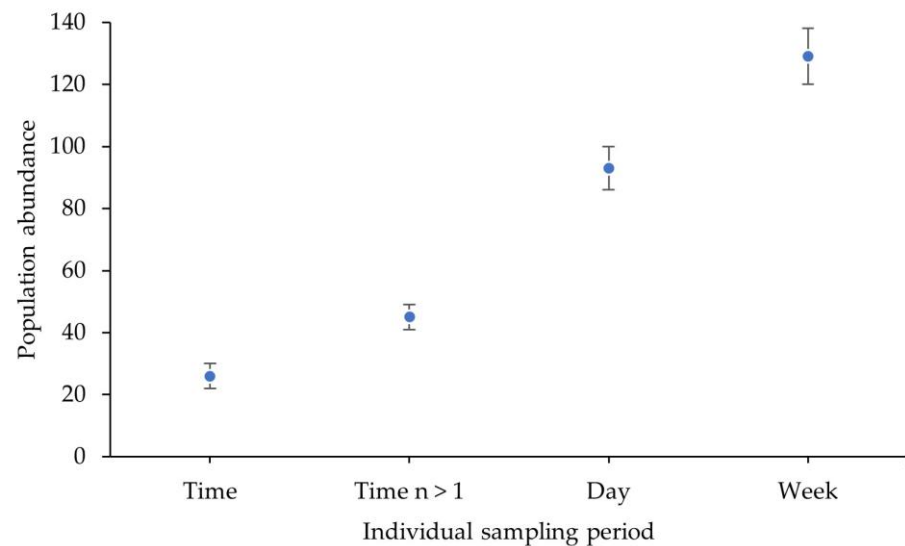


Figure 6. Average abundance $\pm$ 95 % confidence interval of the bighorn sheep (*Ovis canadensis* Shaw) population in the coastal region of the Sierra Santa Isabel in Baja California, Mexico, obtained from different sampling periods.

In terms of population structure, a similar age and sex class ratio was observed in the one-hour, one-hour capture periods with more than one sheep per record and one-day capture periods. It was found that the number of rams was double that of ewes, and that for every 10 ewes, there was one yearling and two lambs (Table 1). The age and sex class ratio obtained from the weekly samples collected indicated that the proportion of rams in the population was lower than that of ewes. However, as in the other sampling periods, it was observed that for every 10 ewes, there was one yearling and two lambs. Statistical comparison of the age-sex class ratio revealed that there was no difference between the proportion of males obtained from the different sampling periods (Kruskal-Wallis, $p \geq 0.05$). However, a difference was observed in the

Table 1. Population abundance of bighorn sheep (*Ovis canadensis* Shaw) according to sex and age in the Sierra Santa Isabel, Baja California, Mexico, for different sampling periods.

Sex and age classification	Sampling period											
	Time			Time n > 1			Day			Week		
	$\bar{x}$	σ	Me.	$\bar{x}$	σ	Me.	$\bar{x}$	σ	Me.	$\bar{x}$	σ	Me.
Ram	21	20	17	23	25	15	22	30	12	8	1	8
Ewe	10			10			10			10		
Yearling	1	2		1	3		1	1	1	1	1	1
Lamb	2	3		2	3	1	2	2	2	2	1	2

$\bar{x}$: mean; σ : standard deviation; Me.: median.

proportion of yearlings (Kruskal-Wallis, $p \leq 0.05$) and lambs (Kruskal-Wallis, $p \leq 0.05$), being higher in the one-day and one-week trapping periods than in the one-hour and one-hour trapping periods with more than one sheep per record.

In the coastal region of the Sierra Santa Isabel, sheep were recorded in different social configurations: solitary, in pairs, and in herds that could be composed of up to 17 animals (Figure 7). The most commonly observed herds consisted of three to five sheep, while groups of six or more animals represented an observation rate of 1 to 2 % each. In terms of sex composition, 35 % of the records were of solitary rams, 17 % of groups of rams, and 13 % of solitary ewes. The other herd types and solitary sheep were observed with a frequency of less than 10 %.

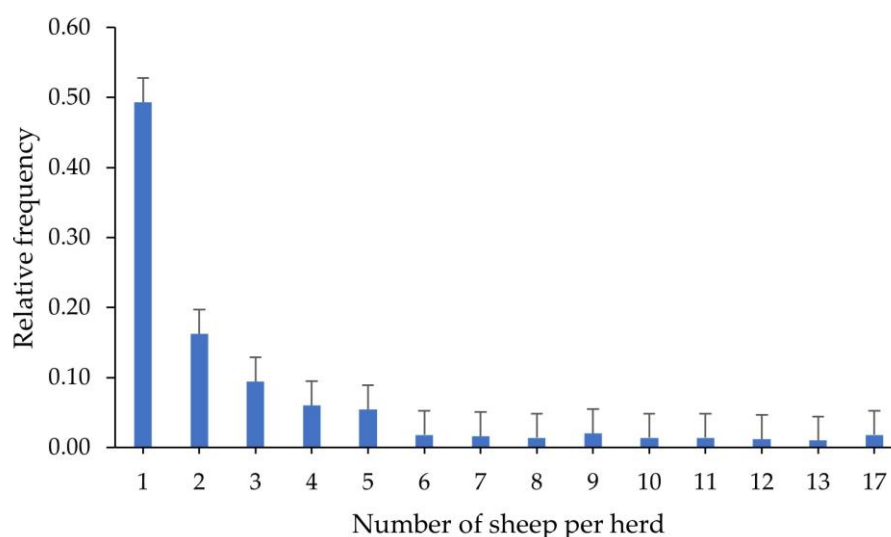


Figure 7. Relative frequency of the number of sheep (*Ovis canadensis* Shaw) that made up the herds recorded in the coastal region of Sierra Santa Isabel, Baja California, Mexico.

Romero-Figueroa *et al.* (2024) conducted an aerial count in the Sierra Santa Isabel, during which they observed 81 sheep and estimated a population abundance of 135 animals using a detectability rate of 60 %. This estimate is within the range of that obtained using trail cameras from independent samples separated by one week taken during the summer (129 ± 9). In the Black Mountains of Death Valley National Park and the Old Dad Mountain of the Mojave Desert, USA, accurate estimates of free-living bighorn sheep population size were also obtained by the Lincoln-Petersen method using camera traps deployed at waterholes during the summer and independently sampled one week apart (Jaeger *et al.*, 1991; Douglass and Longshore, 1995). In this sense, Perry *et al.* (2010) point out that summer is the season in which sampling should be carried out to estimate the bighorn sheep population using trail cameras because arid conditions serve to concentrate most, or all, of the individuals of a population in a few water sources.

Short periods of independent sampling, such as those separated by an hour or a day, tend to underestimate the population of the species because most of the records obtained of bighorn sheep through trail cameras correspond to solitary specimens (Perry *et al.*, 2010; Escobar-Flores *et al.*, 2016). Perry *et al.* (2010), who worked with a confined population at a site with artificial waterholes, corrected this bias by eliminating independent samples composed of a single specimen from the analysis. However, in the present study, a positive adjustment in the population estimate was not observed, which is attributed to the fact that in this area, most of the records corresponded to small groups (< 5 sheep), in contrast to the aforementioned study, where the record of large groups (> 5 sheep) was more frequent.

Bighorn sheep sighted in the coastal region of the Sierra Santa Isabel during aerial monitoring in 2021 were recorded at a distance between 12 and 45 km from the waterholes where trail cameras were deployed in 2022 (Romero-Figueroa *et al.*, 2024). This distance between waterholes and animals observed in 2021 is within the home range of desert bighorn sheep in the fall (Longshore and Douglas, 1995; Hoglander *et al.*, 2015), the season in which aerial monitoring was conducted. This suggests that the population monitored in the 2021 flight is the same as that monitored in 2022 in this study.

The ram:ewe:yearling:lamb ratio obtained from independent sampling periods separated by one week (8:10:1:2) is consistent with that reported on the western slope of the Sierra Santa Isabel (5:10:4; Escobar-Flores *et al.*, 2016), on the Sierra de Las Pintas (7:10:1; López *et al.*, 1995), and generally for the states of Baja California (6:10:1:1; Romero-Figueroa *et al.*, 2024) and Arizona (5:10:4; Murphy, 2021). In the rest of the independent sampling periods, the ram:ewe ratio was 20:10. The high proportion of rams obtained from these periods is due to the fact that most of the photographic records were of solitary rams and groups of rams. In this sense, the ram:ewe:lamb:yearling ratio obtained from the short independent sampling periods did not reflect the population structure of the species but rather the intensity with which the different age classes and sexes made use of the areas in which the cameras were deployed.

The structure of bighorn sheep populations responds to their natural dynamics and the intensity of the extractive use to which they are subjected. In pristine populations of the species, there were 10 rams for every 10 ewes (Hansen, 1967). Currently, there are no bighorn sheep populations that maintain this ram:ewe ratio because in all their areas of distribution the species is exploited both legally (sport hunting) and illegally (poaching). In the coastal region of the Sierra Santa Isabel, the local community recognizes the incidence of poaching on their lands (Ruiz-Mondragón *et al.*, 2023). This situation explains the ram:ewe ratio recorded at the site (8:10), which indicates that this is a population from which rams are extracted. On the other hand, bighorn sheep populations inhabiting desert ecosystems are characterized by low proportions of lambs and yearlings because recruitment occurs in boom and bust cycles linked to periods of drought and because these age classes have the highest mortality (Hansen, 1967).

The bighorn sheep population (129 individuals) was higher than estimated in six of the thirteen mountain ranges in Baja California where the species is distributed (Romero-Figueroa *et al.*, 2024): Cucapá (31), Las Tinajas (27), San Pedro Mártir (65), San Francisquito (11), La Asamblea (111), and Las Ánimas (114). Furthermore, it is comparable to that reported in the El Peloncillo (140–160), Fra Cristóbal (150–200), and San Andrés (174) mountain ranges in New Mexico, USA (Ruhl and Rominger, 2021). Likewise, the ram:ewe ratio recorded in the coastal region of the Sierra Santa Isabel (8:10) was higher than that reported for the entire state of Baja California (6:10; Romero-Figueroa *et al.*, 2024) and in the states of Arizona (5:10; Murphy, 2021) and Nevada (5:10; Cox, 2021). The bighorn sheep population in the coastal region of the Sierra Santa Isabel is one of the most abundant in the state of Baja California (Romero-Figueroa *et al.*, 2024) and is comparable in size to those recorded in the mountain ranges of New Mexico, where several management measures are currently being implemented to increase the population of the species (Ruhl and Rominger, 2021). Furthermore, the number of rams per ten ewes is higher than reported in states such as Arizona and Nevada, where bighorn sheep populations are currently stable (Cox, 2021; Murphy, 2021).

In the coastal region of the Sierra Santa Isabel, as in other desert areas where bighorn sheep are distributed (Jaeger *et al.*, 1991; Perry *et al.*, 2010), a higher frequency of photography was observed during the hottest and driest months of the year. This is due to the fact that during the summer, the water consumption of sheep increases, and they require a minimum water intake equivalent to 4 % of their body weight (Monson and Sumner, 1980). This is why, at this time of the year, the surface area of the home range of sheep is reduced and concentrated near available water bodies (Longshore and Douglas, 1995; Hoglander *et al.*, 2015).

The largest number of photographs was recorded at Tinaja del Miramar, which is the largest waterhole in the coastal region of the Sierra Santa Isabel. The same occurred on the western slope of the Sierra Santa Isabel, where the most commonly used water body is found (Escobar-Flores *et al.*, 2016). The species' preference for water holes

with the highest water volume is explained by the concentration of dissolved solids, the increase of which reduces water quality. In the Sierra Santa Isabel, smaller water holes have a higher concentration of dissolved solids that increases in the dry season when water volume is reduced (Escobar-Flores *et al.*, 2016). The decrease in records on the trail is attributed to the fact that, in June and July, the sheep concentrated their activities around the troughs that have water year-round. As for the Cinco Islas watering hole, its use decreased in the hottest months, as the amount of water in the hole during April and May decreased considerably by June and July.

CONCLUSIONS

The bighorn sheep population estimate calculated with the Lincoln-Petersen method using trail cameras deployed at waterholes during the summer and with independent samples separated by one week was comparable to that previously reported for the area using aerial monitoring. Likewise, the population structure obtained from this estimate was consistent with that expected for a free-living desert bighorn sheep population. Capture periods with independent sampling separated by one hour and one day yielded lower abundances than previously reported for the area, along with an age and sex class ratio that did not reflect the population structure of the species, but rather the use that each of these groups made of the sites where trail cameras were deployed. The abundance of the bighorn sheep population in the coastal region of the Sierra Santa Isabel was 129 ± 9 animals, and the ram:ewe:yearling:lamb ratio was 8:10:1:2. These results suggest that the population of the species at this site is in a good state of conservation.

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