SOLAR EXPOSURE REDUCES PLASMA TESTOSTERONE CONCENTRATIONS, SPERM QUALITY AND FERTILITY IN MALE GOATS FROM SUBTROPICAL LATITUDES †

[LA EXPOSICIÓN SOLAR REDUCE LAS CONCENTRACIONES PLASMÁTICAS DE TESTOSTERONA, LA CALIDAD ESPERMÁTICA Y LA FERTILIDAD EN MACHOS CABRÍOS DE LATITUDES SUBTROPICALES]

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SUMMARY

Background. In subtropical latitudes, where goats are typically raised in rangeland conditions, daily solar radiation may strongly impair reproductive activity in male goats, thus decreasing their fertility. **Objective.** To assess the effects of solar radiation on plasma testosterone concentrations, sperm production and fertility in well-nourished male goats over the course of 1 year. **Methodology**. Control males were kept in a shaded pen (n = 5), whereas the solar-exposed males remained in an unshaded pen exposed to direct solar radiation (n = 5). In experiment 1, plasma testosterone concentrations and sperm production were measured. In experiment 2, fertility of solar-exposed and control males was determined when joined with anestrous female goats. **Results.** Plasma testosterone concentrations varied over time ($P < 0.0001$), and there was an interaction between time and the groups of bucks ($P < 0.001$). In solar-exposed males, testosterone concentrations were lower than controls in June, September, December and January ($P < 0.05$). The total number of spermatozoa per ejaculate and progressive sperm motility varied over time ($P < 0.0001$), but there was no interaction between time and groups ($P > 0.05$). The percentage of live spermatozoa and the percentage of cells with abnormalities varied over time ($P < 0.0001$), and there was an interaction between time and treatment group ($P < 0.0001$). In solar-exposed males, the percentages of live spermatozoa were lower than controls in June, August, November and December, while in May, this percentage was higher in solar-exposed males than in controls ($P < 0.05$). The percentage of abnormal spermatozoa was higher in solar-exposed males than in controls from June to December ($P < 0.001$). The percentage of females that kidded was lower in those joined with the solar-exposed (48%) compared with those joined with control males (79%; $P < 0.001$). **Implications.** Providing shade reduces the negative effects of solar radiation on sperm quality and buck's fertility. **Conclusion.** Daily exposure to solar radiation deeply altered reproductive activity of bucks. Testosterone concentrations, qualitative sperm production and fertility, were much lower in solar-exposed bucks compared to the control bucks kept under shade.

Key words: caprine; reproductive seasonality; sexual behavior**;** sperm production; heat stress; subtropics; endocrine activity; solar exposition.

RESUMEN

Antecedentes. En latitudes subtropicales, donde las cabras se crían típicamente en pastizales, la radiación solar diaria puede afectar considerablemente la actividad reproductiva de los machos cabríos, disminuyendo así su fertilidad. **Objetivo.** Evaluar los efectos de la radiación solar sobre las concentraciones plasmáticas de testosterona, la producción de esperma y la fertilidad en machos cabríos bien nutridos a lo largo de un año. **Metodología**. Los machos control se

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mantuvieron en un corral sombreado (n = 5), mientras que los machos expuestos al sol permanecieron en un corral sin sombra, expuestos a la radiación solar directa (n = 5). En el experimento 1, se midieron las concentraciones plasmáticas de testosterona y la producción de esperma. En el experimento 2, se determinó la fertilidad de los machos expuestos al sol y control al ser empadrados con cabras en anestro. **Resultados**. Las concentraciones plasmáticas de testosterona variaron con el tiempo ($P < 0.0001$), y se observó una interacción entre el tiempo y los grupos de machos cabríos ($P < 0.001$). En los machos expuestos al sol, las concentraciones de testosterona fueron inferiores a las de los controles en junio, septiembre, diciembre y enero ($P < 0.05$). El número total de espermatozoides por eyaculado y la motilidad espermática progresiva variaron con el tiempo ($P < 0.0001$), pero no hubo interacción entre el tiempo y los grupos ($P > 0.05$). El porcentaje de espermatozoides vivos y el porcentaje de células con anomalías variaron con el tiempo ($P < 0.0001$), y hubo una interacción entre el tiempo y el grupo de tratamiento ($P < 0.0001$). En los machos expuestos al sol, los porcentajes de espermatozoides vivos fueron inferiores a los controles en junio, agosto, noviembre y diciembre, mientras que en mayo, este porcentaje fue superior en los machos expuestos al sol que en los controles ($P < 0.05$). El porcentaje de espermatozoides anormales fue superior en los machos expuestos al sol que en los controles de junio a diciembre ($P < 0.001$). El porcentaje de hembras que parieron fue menor en las que se unieron a los machos expuestos al sol (48%) en comparación con las que se unieron a los machos control (79%; $P < 0.001$). **Implicaciones.** Proporcionar sombra reduce los efectos negativos de la radiación solar en la calidad del esperma y la fertilidad de los machos. **Conclusión**. La exposición diaria a la radiación solar alteró profundamente la actividad reproductiva de los machos. Las concentraciones de testosterona, la producción cualitativa de esperma y la fertilidad fueron mucho menores en los machos expuestos al sol en comparación con los machos control mantenidos a la sombra.
Palabras clave: caprino, estacionalidad reproductiva, comportamiento sexual, producción de esperma, estrés térmico, subtrópicos, actividad endocrina, exposición solar.

INTRODUCTION

Male goats from subtropical latitudes exhibit seasonal variations in their endocrine and sexual activities. In these bucks, the breeding season begins in early summer and ends in late winter (Walkden-Brown *et al*., 1994; Delgadillo *et al.,* 1999; Giriboni *et al.,* 2017). This reproductive seasonality is primarily regulated by annual photoperiodic changes (Delgadillo *et al.,* 2004). However, other factors, such as undernutrition (Walkden-Brown *et al.,* 1994; Hötzel *et al.,* 2003) or long-time exposure to solar radiation could dramatically reduce the sexual activity, sperm production and fertility in male goats and rams (Mohamed *et al.,* 2012; Küçük *et al*., 2020; García-Cruz *et al*., 2022). Undernutrition and daily exposure to solar radiation are common in subtropical regions where most animals are managed in semi-extensive systems (Lassoued and Rekik 2005; Delgadillo and Martin 2015; Aboul-Naga *et al.,* 2021). In male goats from subtropical Mexico, for example, testicular diameters, plasma testosterone concentrations, sexual behavior intensity, and both quantitative and qualitative sperm production were lower in males kept in a semi-extensive management system than in well-nourished males kept indoor (García-Cruz *et al*., 2022). However, in this latter study, it is unclear whether these differences were due to undernutrition, daily exposure to solar radiation, or an interaction between these two factors. Therefore, the objective of the present study was to determine plasma testosterone concentration, sexual behavior, sperm production and fertility in well-fed bucks kept indoors and either long-time exposed or not to solar radiation. It was hypothesized that testosterone concentrations, sperm production and fertility would be lower in bucks exposed to solar radiation than in those kept in a shaded pen. To test this possibility, in experiment 1, plasma testosterone concentrations and sperm production were determined in solar-exposed bucks and compared them with those kept in a shaded pen. In experiment 2, fertility in solar-exposed bucks were determined when joined with seasonally anestrous goats, in comparison with those kept in a shaded pen.

MATERIALS AND METHODS

Climatic and general conditions of the study

The study was conducted in the Laguna region of Coahuila, in the subtropical north of Mexico (Latitude 26° 23' N; Longitude 104° 47' W) characterized by a dry, semi-arid climate. In this arid region, the photoperiod ranged from 13 h 41 min of light at the summer solstice to 10 h 19 min of light at the winter solstice. During the first experiment, weekly ambient temperatures as well and relative humidity were registered daily using two digital thermometers placed in both shaded and unshaded pens. The temperature-humidity index (THI) was calculated using the equation: $THI = (0.8) \times DBT + (RH) \times (DBT\text{-}14.4) + 46.4$, where DBT is the dry bulb temperature (°C) and RH is relative humidity in decimal form (Habeeb *et al*., 2018). Humidity was included because animals lose heat through respiration and sweating (Silanikove, 2000). Local male and female goats (*Capra hircus*) from the Laguna region were used, whose origin and phenotypic characteristics have been previously described (Duarte *et al.,* 2008). In bucks from this population, the breeding season lasts from June to

December, while in females, it lasts from September to February (Delgadillo *et al*., 1999; Duarte *et al.,* 2008). All animals were fed 2 kg lucerne hay/buck.day (9.6 $MJ*kg^{-1}$, 18% crude protein$*kg^{-1}$ dry matter), providing a maintenance diet (National Research Council, 2007).

Experiment 1: Plasma testosterone concentrations, testicular diameter and qualitative and quantitative sperm production in well-nourished male goats with or without direct solar exposure

Bucks and experimental design

Male goats that were 4 years old at the beginning of the study were used. Starting on 15 March, bucks were assigned to two groups (n = 5 each), balanced for body weight (BW), testicular diameter and progressive sperm motility (García-Cruz *et al.,* 2022). Control males were placed in a shaded pen (6 x 6 m; BW: 71 ± 3 kg; testicular diameter: 108 ± 3 mm; progressive sperm motility: 3 ± 0.1; mean ± SEM), while solar-exposed males were placed in an unshaded pen (6 x 6 m) throughout the study (BW: 72 ± 2 kg; testicular diameter: 108 ± 4 mm; progressive sperm motility: 3 ± 0.2). Due to the high cost of maintaining adult bucks, five animals per group were used, as a previous study showed that this number was sufficient to reveal significant endocrine and sexual differences between bucks kept in a semi-extensive management system or indoors (García-Cruz *et al.,* 2022).

Measurements

Rectal temperature and respiratory rate

Rectal temperature and respiratory rate were measured every 15 days at the same time (13:00), with animals being prevented from consuming food or water at the time of recording. Rectal temperature was measured using a clinical thermometer with an accuracy of ± 0.1 °C for 1 min and respiratory rate was measured visually by counting the flank movements for 1 min from three meters while the animal was standing quietly (Gaughan *et al.,* 2000).

Heat stress evaluation

To determine if the animals were experiencing heat stress, the degree of heat stress was classified according to respiratory frequency: low: 40–60 breaths per min; medium-high: 61 to 80 breaths per min; high: 81 to 120 breaths per min; severe heat stress: more than 120 breaths per min (Silanikove, 2000).

Body weight, testicular diameter and plasma testosterone concentrations

Body weight, testicular diameter and plasma testosterone concentrations were measured every two weeks from 15 March to 28 February of the next year. All variables were measured in the morning by the same operator, before the distribution of lucerne hay. Body weight was determined using a manual balance with a capacity of 150 kg and a precision of 0.05 kg (Torrey; Nuevo León, México). Testicular diameter was measured using a millimeter caliper, recording the greatest width of both testicles (Oldham *et al.,* 1978). Plasma testosterone concentrations were determined in blood samples obtained via jugular venipuncture, using tubes containing 30 µL of heparin. The blood samples were centrifuged at 2500 X g for 20 min, and the resulting plasma was stored at -20 ºC until assayed by direct enzyme immunoassay (Delgadillo *et al.,* 2024). The sensitivity was 0.3 ng/mL, and the intra-assay CV was 8.7%.

Ejaculation latency and sperm production

Ejaculation latency and sperm production were assessed during the last 4 days of May and June (beginning of the breeding season), August and September (mid-breeding season), and November and December (end of the breeding season) when the males were exposed to an intact, estrus-induced goat (Delgadillo *et al*., 1999). Males were trained to ejaculate into an artificial vagina in December of the previous breeding season. One ejaculate per male was collected in each session. To determine ejaculation latency, bucks were given 3 min to ejaculate after exposure to the female. The bucks were handled in the same order, and prior to each evaluation period, males were collected twice a week to avoid potential effects of not collecting ejaculates over an extend period. All bucks ejaculated during each solicitation. The total number of spermatozoa per ejaculate was calculated by measuring the ejaculate volume and sperm concentration using a photometer (Goat SpermaCue; Minitube, Tiefenbach, Germany). Progressive sperm motility was evaluated in undiluted samples after semen collection using a phase-contrast microscope (Scale: 0-5; Delgadillo *et al.,* 1999). The percentage of live spermatozoa was assessed using the eosin-nigrosin staining procedure on undiluted sperm samples (5 µL). A total of 200 sperm cells from each sample were observed for live (unstained) or dead (stained) sperm heads. Sperm morphology was evaluated by counting a total of 200 sperm cells from each sample under a phase-contrast microscope at X 100 magnification (Farshad *et al.,* 2012).

Experiment 2: Sperm production, sexual behavior and fertility of well-nourished male goats with or without direct solar exposure

Bucks and experimental design

In this study, the same males from the Experiment 1 were used, which were kept in the same group and conditions as described in experiment, and were joined with anestrous goats (male effect) to determine their fertility. Therefore, on 12 June (10 days before the male effect), ejaculation latency, progressive sperm motility and percentage of live spermatozoa were determined in all males, as described in Experiment 1. A total of three ejaculates per buck were evaluated before the male effect.

Female groups

Multiparous female goats previously separated from the males since December were used. On 30 May, 10 June and 20 June, the ovulatory status of females was determined using a transrectal ultrasonography with an Aloka SSD-500 device (Aloka Co., Ltd, Tokyo, Japan) connected to a transrectal 7.5-MHz linear probe (Simões *et al*., 2007). Females without a corpus luteum in all three ultrasonographic exams were considered anovulatory and then, were used in the experiment. On 19 June, the females were assigned to two groups (n = 49 each) balanced by body condition score (2.6 ± 0.1 in both groups) using a scale from 1 (very lean) to 4 (obese) (Walkden-Brown *et al.,* 1993). In both groups, the females were separated into five subgroups (n = 9-10) each joined with one male (see the male effect), to avoid fights and accidents, and kept in shaded pens (4 x 4 m each). Each subgroup was separated by an openwork wooden barrier, allowing visual, olfactory, and nose-to-nose contact among animals. The females were milked once daily throughout the study.

The male effect

On 20 June, 48 h before being joined with males, all females were treated with 25 mg IM of progesterone (Facilgest 25 mg*mL^{-1}; Syva Laboratory) to reduce the frequency of short-duration ovulatory and estrous cycles and induce estrus behavior at the first ovulation (Andrade-Esparza *et al.,* 2018). On 22 June (Day 0), one group of females was joined with the control males (n = 5), while the other group was joined with the solar-exposed males (n = 5). The males remained in contact with the females for 15 days.

Measurements during the male effect

Sexual behavior of males joined with female groups

The nudging events displayed by the males were monitored from 8:00 to 8:15 on Day 0 and 1 after their introduction to the female groups (Bedos *et al.,* 2016).

Pregnancy, fertility and prolificacy

Pregnancy rates were determined based on the presence of embryos, as assessed by transrectal ultrasonography performed 50 days after the introduction of males into both female groups (Ponce *et al.,* 2014). Fertility (does kidding/does exposed to bucks) and prolificacy (kids born/does kidding) at parturition were recorded (Delgadillo and Vélez, 2010).

Statistical analyses

Rectal temperature, respiratory rate, body weight, testicular diameter, plasma testosterone concentrations, ejaculation latency, total number of sperm per ejaculate, progressive sperm motility, percentage of live sperm and percentage of abnormal sperm cells were analyzed using two-way repeated-measures ANOVA to detect differences between treatments. The model included the treatment (group), sampling time (weeks), and the interaction between these factors. The total number of nudging events displayed by bucks was compared using a Chi-square test for goodness of fit, with a random distribution of 50% in each group as the null hypothesis. The proportions of pregnant females and fertility were compared between groups using the Chi-square test. Prolificacy was compared between groups using the Mann–Whitney U test. Analyses were performed using the statistical software package SYSTAT Statics (2009). Data are expressed as the mean ± SEM, and differences were considered significant at $P \leq 0.05$.

RESULTS

Experiment 1

Prevailing climatic conditions during the experimental period

In the shaded pen, the mean maximum ambient temperature from April to September was 37.7 ± 0.3 ºC and from October to December, it was 28.7 ± 0.5 ºC. In the unshaded pen, these two means maximum ambient temperatures were higher than those registered in the shaded pen (41.7 ± 0.2 ºC and 32.3 ± 0.6 ºC, respectively; $P < 0.0001$; Figure 1a). In the shaded pen, the mean minimum ambient temperature from April to September was 20.1 ± 0.2 ºC and from

October to December, it was 11.4 ± 0.4 ºC. In the unshaded pen, these two mean minimum ambient temperatures were higher than those registered in the shaded pen (18.5 ± 0.2 ºC and 8.9 ± 0.4 ºC, $P < 0.0001$; $P < 0.001$; respectively Figure 1b).

Temperature and humidity index (THI)

The THI in unshaded pen remained higher than in shaded pen from March to October. In August, the shaded pen registered a THI of 85, while the unshaded pen registered a THI of 100. From August, the THI gradually decreased in both types of pens until December, reaching a value of 70 (Figure 1c).

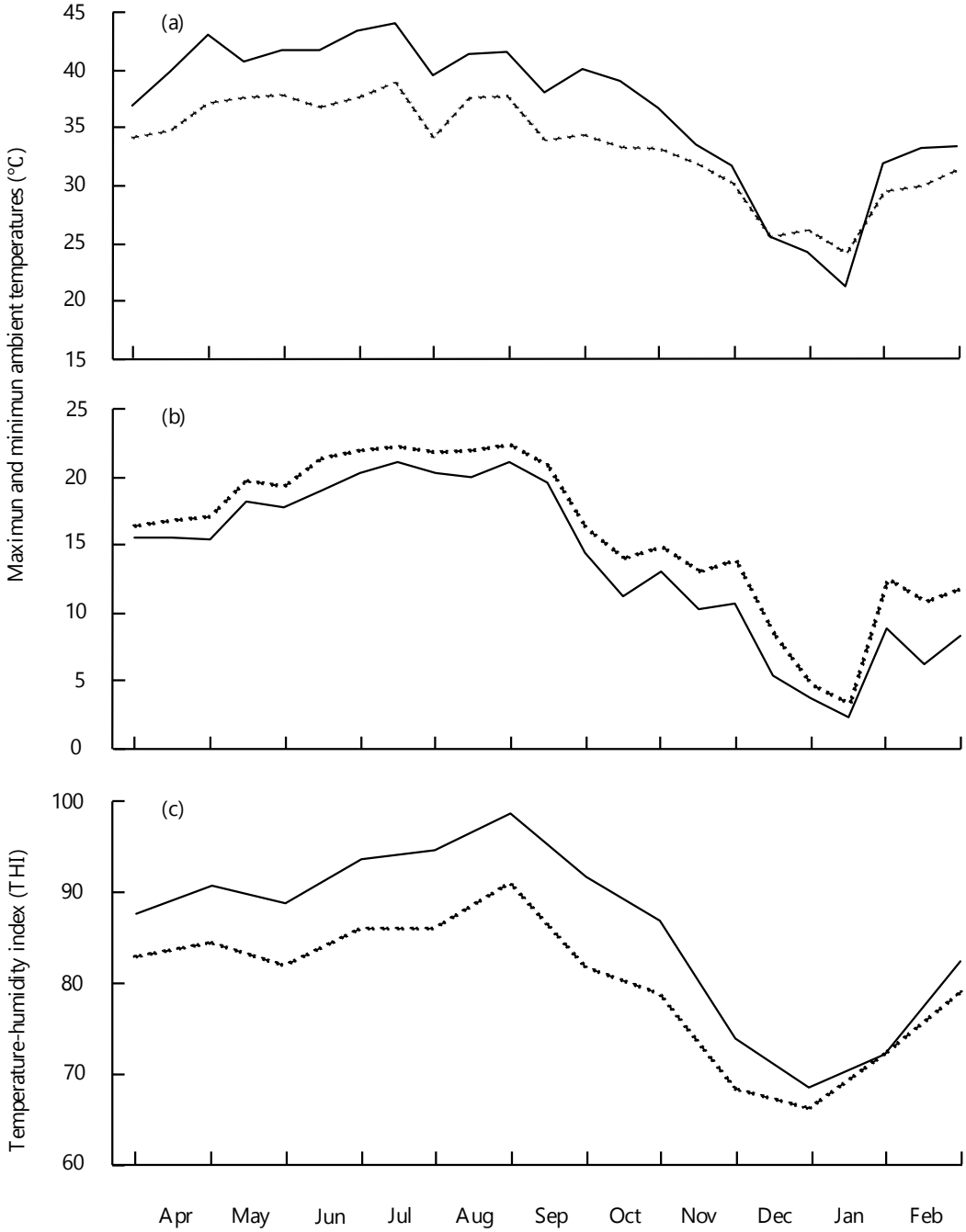

Figure 1. Weekly maximum (a) and minimum (b) ambient temperatures in shaded (dotted line) and unshaded (continue line) pens, and temperature humidity index (THI) (c). The THI values were calculated based on temperature and humidity data from both shaded and unshaded pens.

Rectal temperature and respiratory rate

Rectal temperature and respiratory rate varied over time ($P < 0.0001$), and there was an interaction between time and groups ($P < 0.001$). In the solar-exposed group, rectal temperature was higher in May, August, September, October and February than in the control group ($P < 0.001$; Figure 2a). Similarly, the respiratory rate of the solar-exposed males was higher in all months of the study, except for December, compared to the control group ($P < 0.001$; Figure 2b).

Heat stress evaluation

In the solar-exposed males, heat stress ranged from high to severe between March and November, and from low to medium between December and February. In contrast, the control group remained under low to medium heat stress throughout the study, except in August, when it increased to a high level (Figure 2c).

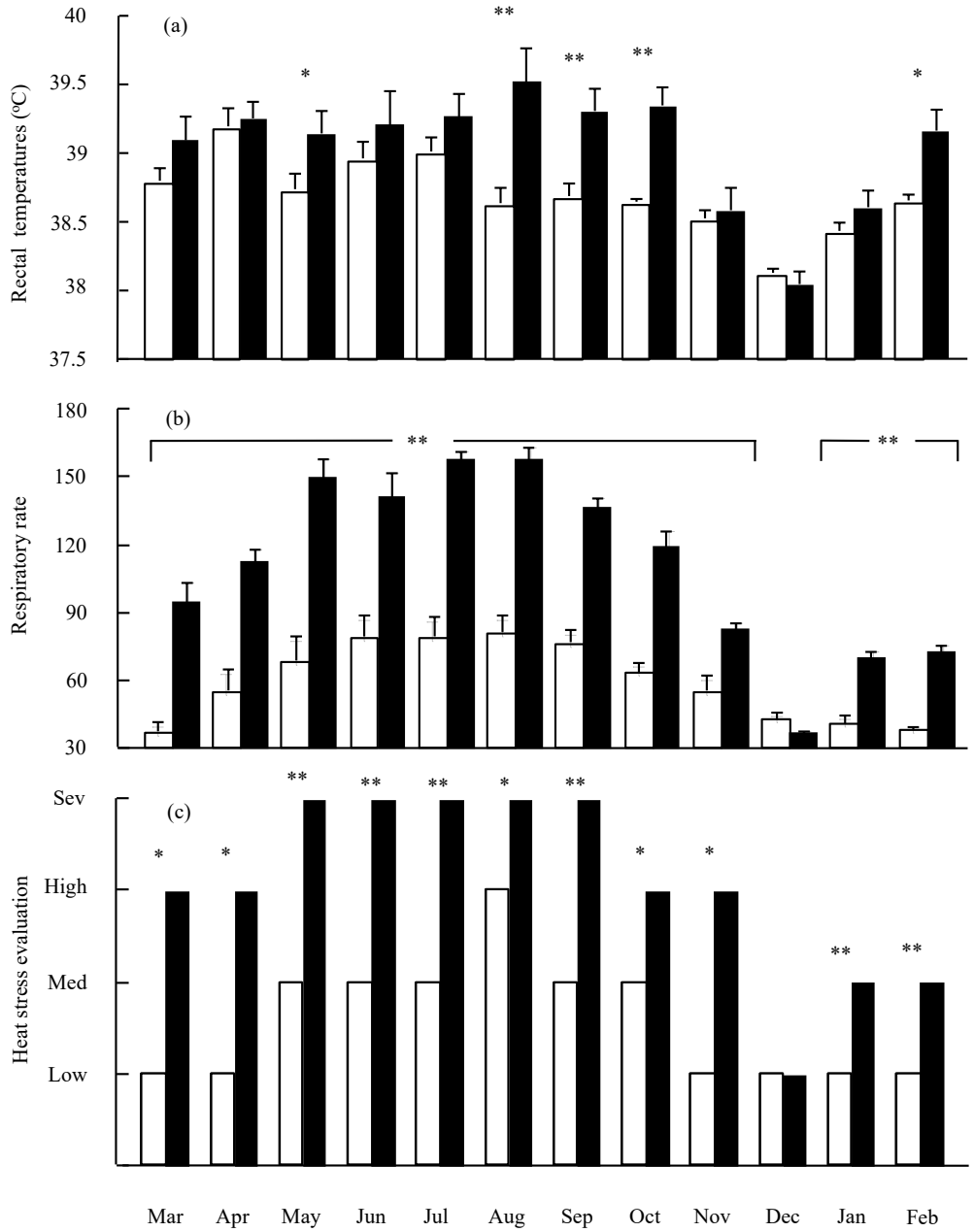

Figure 2. Rectal temperature (a), respiratory rate (b) (mean ± SEM) and degree of heat stress (c) in two groups of male goats. The control group was kept in a shaded pen (□), while the solar-exposed group was kept in an unshaded pen exposed to solar radiation (■). Heat stress evaluation was classified according to respiratory frequency: low, medium-high (Med), high and severe (Sev). All these variables were measured every two weeks. *P < 0.05; **P < 0. 01.

Body weight, testicular diameter, and plasma testosterone concentrations

In both groups, body weight varied over time ($P < 0.0001$), but there was no interaction between time and group ($P > 0.05$). In both groups, BW increased progressively from March to May, then decreased until October (Figure 3a). Testicular diameter varied over time ($P < 0.0001$), and there was an interaction between time and the group of bucks ($P < 0.001$). In the solar-exposed bucks, testicular values were lower than those of the controls in July and August ($P < 0.05$). In both groups, testicular diameter increased from April to June, then decreased until November (Figure 3b). Plasma testosterone concentrations varied over time ($P < 0.0001$), and there was an interaction between time and the group of bucks ($P < 0.001$). This variable was lower in solar-exposed bucks than in control bucks in June, September, December and January ($P < 0.05$; Figure 3c). In both groups, plasma testosterone concentrations increased in June and remained high until October, then decreased until the end of the study.

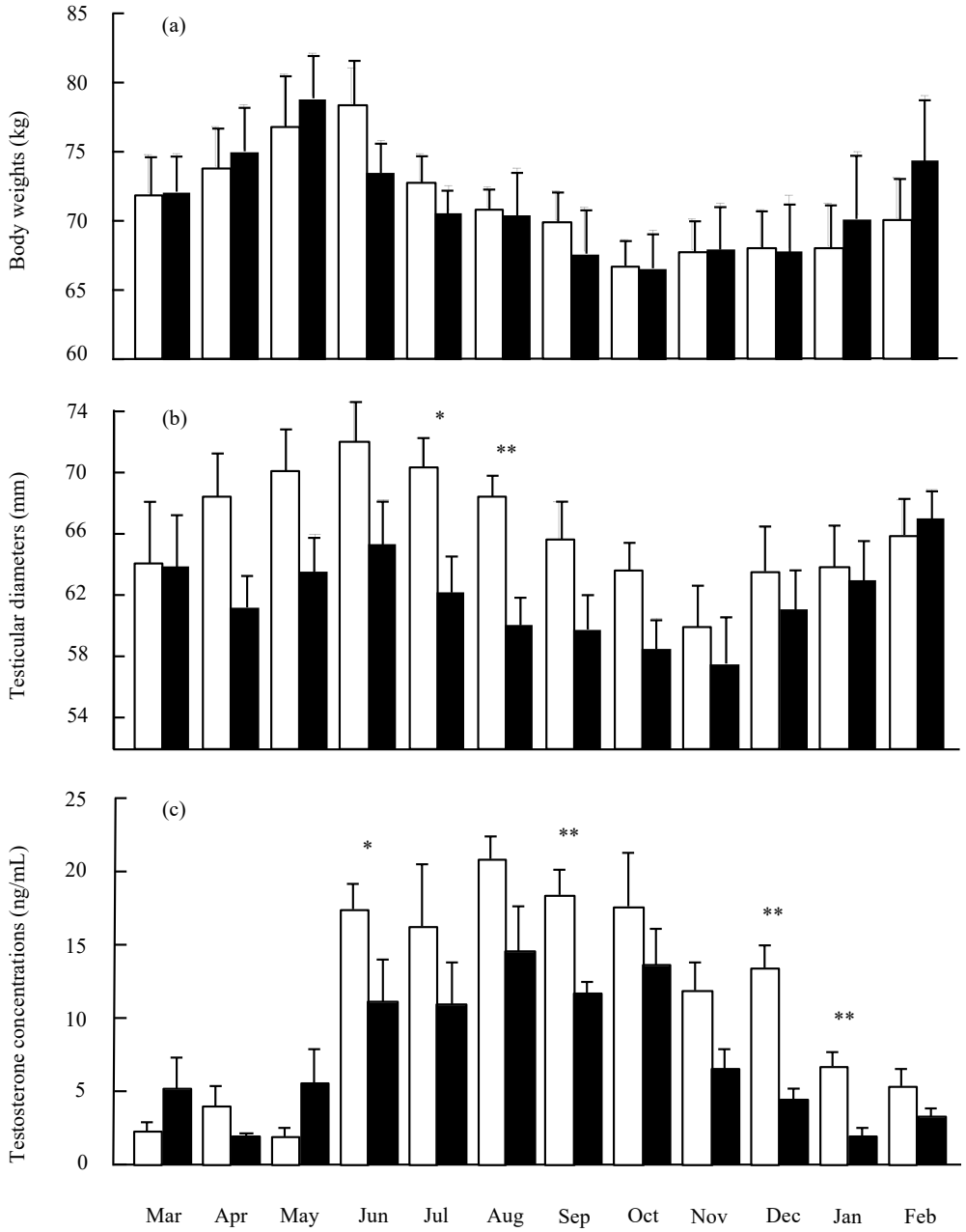

Figure 3. Body weight (a), testicular diameter (b) and plasma testosterone concentration (c) (mean ± SEM) in two groups of male goats. The control group was kept in a shaded pen (□), while the solar-exposed group was kept in an unshaded pen exposed to solar radiation (■). These variables were measured every two weeks. *$P < 0.05$; **$P < 0.01$.

Ejaculation latency and sperm production

Ejaculation latency and all sperm production variables varied over time ($P < 0.0001$). For ejaculation latency, there was no interaction between time and group of bucks ($P > 0.05$; Fig. 4a), and in both groups, the mean values remained below 60 s throughout the study. For the total number of spermatozoa per ejaculate, there was no interaction between time and group of bucks ($P > 0.05$; Figure 4b), and in both groups, the mean values remained relatively stable throughout the study.

For progressive sperm motility, there was no interaction between time and group of bucks ($P < 0.0001$; Figure 5a), and in both groups, this variable increased from June and remained elevated until September. For the percentage of live spermatozoa, there was an interaction between time and group of bucks ($P < 0.0001$), and this variable was lower in the solar-exposed than in controls bucks in June, August, November and December. However, in solar-exposed bucks, this percentage was higher than in controls in May ($P < 0.05$; Figure 5b). For the percentage of abnormal sperm cells, there was an interaction between time and group of bucks ($P < 0.0001$; Figure 5c) and these percentages were higher in solar-exposed than in control bucks from June to December ($P < 0.001$).

Experiment 2

Ejaculation latency and sperm production before the male effect

Ejaculation latency did not differ between solar-exposed and control bucks (34 ± 2 *vs.* 18 ± 4 s, respectively; $P > 0.05$), nor did progressive sperm motility (2.0 ± 0.3 *vs*. 3.6 ± 0.0; $P > 0.05$). In contrast, the percentage of live spermatozoa was lower in solar-exposed compared with the control bucks (37 ± 4 *vs.* 65 ± 2, respectively; $P < 0.0001$).

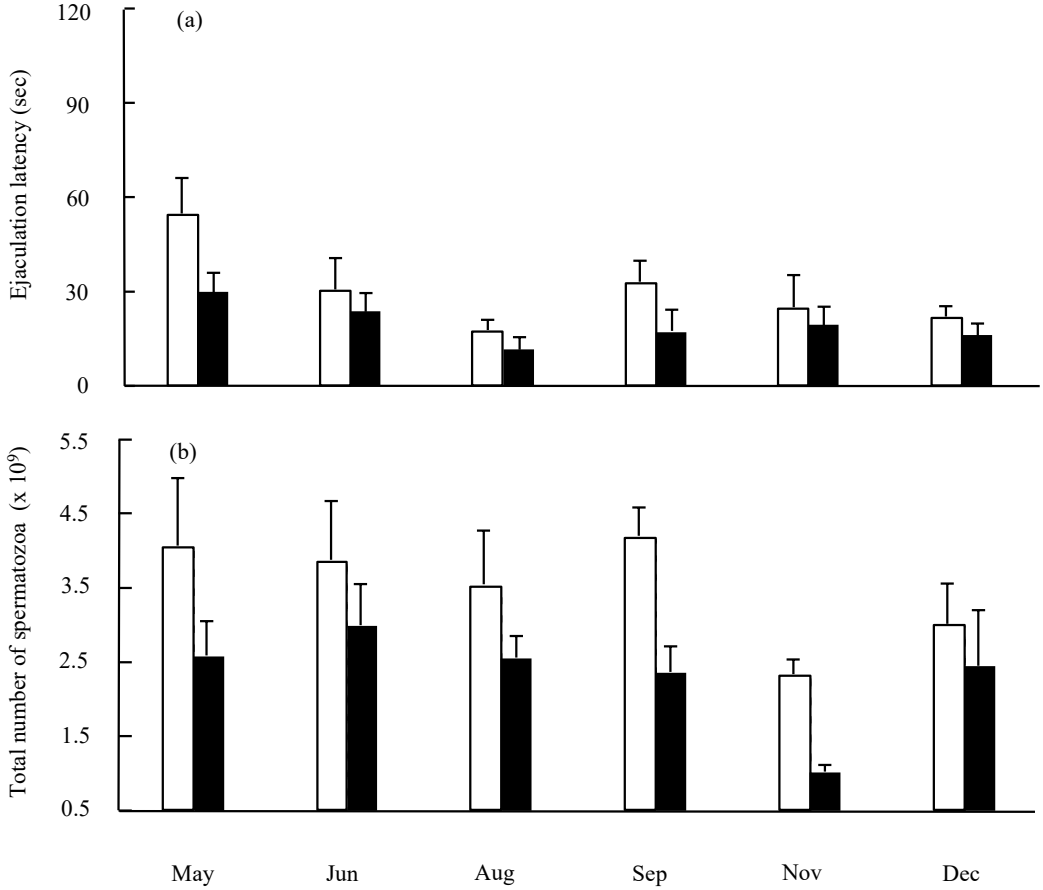

Figure 4. Ejaculation latency (a) and the total number of spermatozoa per ejaculate (b) (mean ± SEM) in two groups of male goats. The control group was kept in a shaded pen (□), while the solar-exposed group was kept in an unshaded pen exposed to solar radiation (■). Bucks were given 3 min to ejaculate after exposure to the female. These variables were assessed in all animals during the last four days of May and June (beginning of the sexual season), in August and September (mid-breeding season) and in November and December (end of the breeding season).

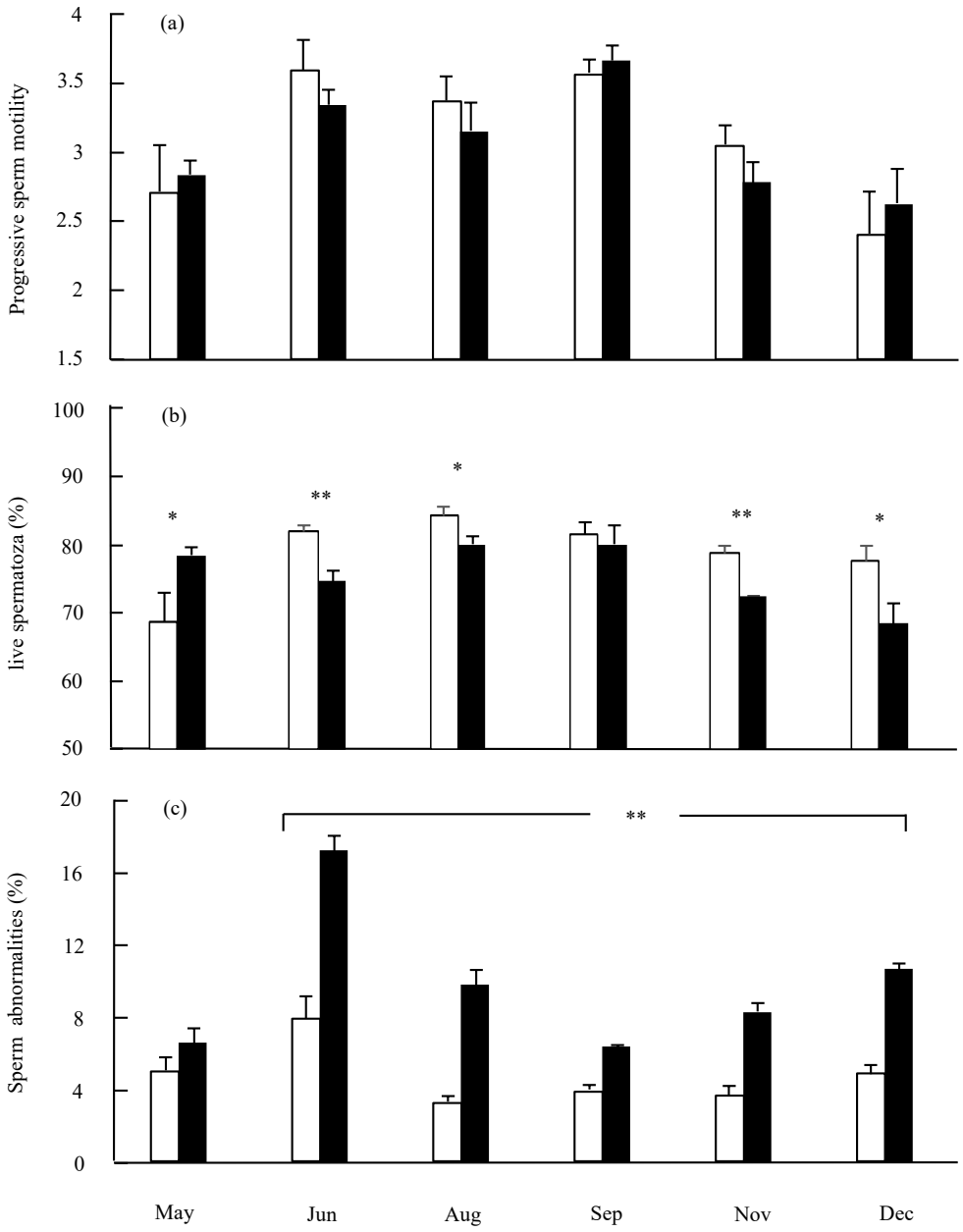

Figure 5. Progressive sperm motility (a) (mean ± SEM), percentage of live sperm (b), and percentage of abnormal spermatozoa in two groups of male goats. The control group was kept in a shaded pen (□), while the solar-exposed group was kept in an unshaded pen exposed to solar radiation (■). These variables were assessed in all animals during the last 4 days of May and June (beginning of the sexual season), in August and September (mid-breeding season) and in November and December (end of the breeding season). P < *0.05; *P < 0.01.

Sexual and reproductive responses of male and females during the male effect

Sexual behavior of bucks

The total number of nudging events performed by the solar-exposed and control males did not differ between groups (373 *vs.* 415, respectively; P > 0.05).

Pregnancy, fertility and prolificacy

The percentage of pregnant females was lower in those joined with solar-exposed males than in females joined with control males (67%; 33/49 *vs.* 85%, 42/49; P < 0.05). Similarly, the percentage of females that kidded was lower in those joined with solar-exposed males than in those joined with control males (48%; 24/49 *vs.* 79%; 39/49; P < 0.001). In contrast, prolificacy did not

differ between groups (solar-exposed males: 1.4 ± 0.1; control males: 1.7 ± 0.0; P > 0.05).

DISCUSSION

The results of these studies show that prolonged exposure of bucks to solar radiation decreases the percentage of live spermatozoa, increases sperm abnormalities, and reduces the males' ability to fertilize females. Other sexually determined variables, such as testosterone concentrations, sexual behavior, and quantitative sperm production, were only slightly affected by solar exposure. Therefore, prolonged exposure to solar radiation reduces the reproductive capacity of male goats. In this study, the THI index was higher in unshaded that in shaded pens and the solar-exposed males showed an increase in body temperature and respiratory rate in an attempt to counteract the effects of heat stress. Therefore, it is likely that the heat stress experienced by solar-exposed males caused the decline in sperm quality.

In Experiment 1, the testicular diameter of males from both control and solar-exposed groups varied similarly, with no significant differences at most individual time points. These variations coincide with those previously reported in males from subtropical latitudes (Walkden-Brown *et al.,* 1994; García-Cruz *et al.,* 2022). The lack of differences in testicular diameter between groups is likely due to similar patterns in live weight variations between control and solar-exposed groups (Walkden-Brown *et al.,* 1994; Delgadillo *et al.,* 1999; García-Cruz *et al*., 2022). The absence of differences in body weight suggests that exposure to solar radiations likely did not reduce food intake, consistent with findings in other studies of male goats and rams (Abdel-Samee, 2009; Al-Tamimi, 2005; De *et al.,* 2017). In both groups, testosterone plasma concentrations followed a similar pattern, with only occasional decreases in solar-exposed males compared to the controls. In the solar-exposed males, it is likely that solar radiation and high temperatures induced a reduction in steroidogenesis at the testicular level, leading to lower testosterone concentrations (Bozkaya *et al.,* 2017). Despite the differences in testosterone concentrations, ejaculation latency, a measure of sexual behavior, did not differ between control and solar-exposed males throughout the study, suggesting that testosterone levels were sufficient to maintain sexual behavior at a similar intensity in both groups. This hypothesis is supported by findings indicating that male goats and rams exposed to short photoperiodic cycles maintain intense sexual behavior year-round, despite having lower testosterone levels than males exposed to natural photoperiod variations (Pelletier and Almeida, 1987; Delgadillo and Chemineau, 1992). Another interesting observation is that testicular diameter, testosterone concentrations and sexual behavior in solar-exposed males were higher than those reported in the same population kept in a semi-extensive production system, where males grazed daily for 7 hours under direct solar radiation and were undernourished during the breeding season (García-Cruz *et al.,* 2022). These results, along with those of Cruz-García *et al*. (2022) suggest that undernutrition, rather than daily exposure to solar radiation, is the primary factor responsible for the reduction of these variables in males kept in a semi-extensive production system. Taken together, these findings indicate that in well-nourished male goats, prolonged exposure to solar radiation reduces plasma testosterone concentrations only in certain months, but does not affect sexual behavior, likely because these males are well-adapted to high ambient temperatures.

The total number of spermatozoa per ejaculate, a measure of quantitative sperm production, did not differ between the control and solar-exposed groups. These results indicate that in solar-exposed males, solar radiation did not reduce spermatogenic efficiency in terms of quantitative sperm production. This finding contrasts with studies in Santa Inês rams exposed to solar radiation (Teodoro *et al.,* 2013) but aligns with others in which males were exposed to warm environments and high temperatures (Al-Hozab and Basiouni, 1998). This is further supported by the fact that testicular diameter, an indicator of spermatogenic activity in male goats and rams (Oldham *et al.,* 1978; Delgadillo *et al.,* 1993), did not differ between solar-exposed and control males throughout the study. In contrast, sperm quality, as assessed by the percentage of live sperm and sperm abnormalities, was significantly affected by prolonged exposure to solar radiations. This finding is consistent with results reported in male goats (Mohamed *et al.,* 2023), and other species, including boars (Kunavongkrit *et al.,* 2005), bulls (Rizzoto and Kastelic, 2020) and rams (Hamilton *et al.* 2016). In these species, solar radiation or high ambient temperatures induced heat stress (Rizzoto and Kastelic 2020; Hamilton *et al.,* 2016), leading to degeneration of the germinal epithelium, partial atrophy of seminiferous tubules, germ cell apoptosis and sperm DNA damage (Paul *et al.,* 2008; Kanter *et al.,* 2011; Shahat *et al.,* 2020), ultimately disrupting spermatogenesis. Moreover, heat stress often disrupts the normal functioning of the epididymis and causes damage to sperm cells via oxidative stress, which leads to mitochondrial dysfunction in epididymal sperm (Shahat *et al.,* 2020). In this study, it is likely that one or more of these described processes contributed to the decrease in the percentage of live sperm and the increase in sperm abnormalities.

Progressive sperm motility did not differ between the groups, despite the high ambient temperatures registered from April to September. This suggests that

these males are well adapted to high temperatures, as previously reported (Al-Hozab and Basiouni, 1998). Adaptation to high temperatures is likely due to compensatory effects on sperm production and sperm motility, but not on live sperm or sperm morphology. This leads a general decrease in fertility.

In Experiment 2, fertility in females joined with the solar-exposed males was lower than in those joined with the control bucks. This reduced fertility was likely due to the significant decrease in the percentage of live spermatozoa observed in the solar-exposed bucks, as previously reported in rams (Colas, 1981).

CONCLUSION

The results of these studies indicate that, in male goats, exposure to solar radiation dramatically decreases the percentage of live sperm and increases the sperm abnormalities, reducing the males' ability to fertilize females. These findings are of practical significance and could explain the low fertility observed in female goats raised in semi-extensive production systems and joined with males that are daily exposed to solar radiation and high ambient temperatures through the year.

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Data availability. The data that support the findings of this study are available from the corresponding author (joaldesa@yahoo.com) upon reasonable request.

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