Maternal Activity Patterns in Snow Leopards (*Panthera uncia)*

Temporal Shifts Across Cub Development and Their Conservation Implications

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Maternal Activity Patterns in Snow Leopards (*Panthera uncia).* Temporal Shifts Across Cub Development and Their Conservation Implications.

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Abstract

Understanding the behavioural ecology of reproductive female snow leopards (*Panthera uncia)* is critical to improving conservation efforts for this elusive and vulnerable species. This study investigates how maternal snow leopard activity patterns shift across reproductive stages and cub development, using GPS collars equipped with dual-axis accelerometers to capture high-resolution movement and activity data. Two complementary analytical approaches, activity overlap analysis and Generalised Additive Models (GAMs), were employed to examine diel rhythms in relation to reproductive status. Findings reveal that reproductive females exhibit significantly altered activity patterns compared to non-reproducing counterparts, particularly during the denning phase. Activity is notably reduced during dawn and night, with a distinct dusk peak and a recurring midday activity component in early cub rearing. These patterns gradually shift and elevate as cubs mature, with crepuscular rhythms re-emerging and overall activity increasing in response to growing energetic demands. Temporal behaviour was closely aligned with cub developmental milestones, including increased mobility and the transition to solid food. These insights have clear conservation relevance. Denning females face heightened physiological and ecological vulnerability, which may be exacerbated by climate change and human disturbance in multi-use landscapes. Recognising these fine-scale behavioural shifts enables more targeted conservation interventions, such as minimizing disturbance during denning periods and maintaining access to water and secure habitat. This study highlights the value of integrating behavioural ecology into conservation planning, especially for solitary carnivores with extended maternal investment.

Keywords: Accelerometer data, Conservation implication, Cub dependency, Cub development, Diel activity patterns, Denning, Felid, Maternal behaviour, Reproductive ecology, Reproductive stages, Reproductive trade-off, Solitary carnivore, Snow leopard, Wild cat ecology

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1. Introduction

Activity patterns are an underlying feature of an animal's ecology that reflect how the animal interacts with their environment to meet their physiological and ecological needs (Daan & Aschoff 1975). Animals need to balance their activity in relation to predation risk, foraging efficiency, competition and reproductive status, which directly influence these patterns. When and how animals choose to be active or resting can vary both between species and among individuals depending on what environmental factors are shaping these activity patterns (Halle 2000). Carnivores, in particular, offer compelling insights into activity ecology because their patterns are shaped not only by environmental conditions and energetic demands, but also by the need to optimize hunting success while avoiding competition and human conflicts (Curio 2012; Ordiz et al. 2013; Carter et al. 2015). They have low reproductive rates and long parental investment periods (Gittleman 1986; Sunquist & Sunquist 2002), often exhibit flexible diel rhythms (Carter et al. 2015) and require large spaces of land to live in, making them indicator species in landscape conservation (Ripple et al. 2014).

Among seasons and thermoregulation there are many factors that can affect a large carnivore’s daily activity, such as the need to avoid competition (Hayward & Hayward 2007), predator-prey interactions (de Matos Dias et al. 2018), human interactions (Carter et al. 2015) and sex-specific factors like reproductive status (Schmidt et al. 2009). However, studies on specific changes in female behaviour and activity related to the production of offspring are relatively rare. To protect offspring and facilitate nursing, a reproductive female may reduce her home range and movement (Schmidt et al. 2009; Olson et al. 2011; Jędrzejewski et al. 2021). Even though her movement is constrained, the female’s activity may increase due to the energy demands of rearing young and the foraging needed to match this (Balme et al. 2017; Jędrzejewski et al. 2021). Reproductive females may also shift the timing of their activity towards periods of lower risk or higher prey vulnerability and selecting habitats more suitable for denning with little disturbance (Conde et al. 2010).

Large carnivores play a crucial role in maintaining healthy ecosystems through top-down regulation of prey populations and by shaping trophic dynamics across landscapes (Ripple et al. 2014; Fox et al. 2024a). They are considered keystone species in ecological systems by limiting herbivore populations, influencing vegetation structure and promoting biodiversity (Terborgh & Estes 2013). Their declining populations, mainly due to fragmentation of land, habitat loss, human-wildlife conflicts and exploitation are cause for alarm (Ripple et al. 2014). Felid species, particularly solitary ones, are among the most heavily impacted. Their ecological importance is matched by their vulnerability, as they require large, undisturbed territories and are especially susceptible to threats like poaching and retaliatory killing in response to livestock predation (Ordiz et al. 2013; Ripple et al. 2014; Macdonald et al. 2015). Like many carnivores, felids have a general trade-off between the gains of resources like food and interactions with mates and the cost of competition, poor weather and human interactions (Macdonald et al. 2015; Johansson et al. 2022). Females with dependent young have an additional trade-off which is between the reproductive success and health of the female and the effort invested in her current offspring's survival and fitness (Harshman & Zera 2007). This sex-specific trade-off may influence the activity patterns of solitary hunters with dependent young in addition to the factors mentioned above. The snow leopard (*Panthera uncia),* living as an apex predator, is an excellent representative of solitary carnivores and is one of the least studied of the large wild cats (McCarthy et al. 2005; Thomas McCarthy & David Mallon 2016). Female snow leopard's activity is extremely limited and with the snow leopard population threatened and in decline, ecological studies on the species are of great value (Jackson (SLC) et al. 2016).

Snow leopards have been known to show discretional nocturnal activity, not uncommon from other large felids (Jędrzejewski et al. 2021; Johansson et al. 2022), with activity peaks during dusk and dawn (Sunquist & Sunquist 2002). According to Johansson et al. (2022) these activity peaks change seasonally as the snow leopards adjust to ambient temperatures. There so little known on the reproduction of wild snow leopards and large carnivores in general (Balme et al. 2017). Thus, it is of high importance to gain empirical knowledge and understanding of the costs and gains of reproduction and the behaviour of reproductive females to assist the conservation efforts for this vulnerable and elusive animal (Johansson et al. 2020). Snow leopard cubs are dependent on their mother for up to two years (Johansson et al. 2020). This is quite an investment of time and effort on the mother's side, highlighting the importance and sensitivity of rearing young snow leopards and making the species one of few solitary felids to have such a late separation time (Johansson et al. 2020). High amounts of the female's energy is spent on raising her young and the energy input varies depending on the reproductive stage of the female and the developmental stage of her young (John L. Gittleman & Steven D. Thompson n.d.). Early stages of the cubs' lives require a lot of energy because the female is lactating, and the cubs are born semi-altricial (Laurenson 1994; Olson et al. 2011; John L. Gittleman & Steven D. Thompson n.d.). It has been found that snow leopard females do constrain their movement (home range size) and show specialised activity patterns during reproduction, particularly around the early stages of cub rearing; and that extended maternal care is given under harsh conditions (Johansson et al. 2020; Pålsson 2022). The studies supporting these findings do emphasize the need to focus on more detailed denning behaviour, cub development, variation in maternal strategies and females' response to disturbance during reproduction (Johansson et al. 2020; Pålsson 2022). Snow leopards are skilled ambush hunters and it takes persistence and time to develop the skills needed to become an independent snow leopard (Johansson et al. 2022; Fox et al. 2024a). A mother's protection, experience and her cub-raising strategy is likely one of the most influential factors for juvenile snow leopard's survival. However, little is currently known about the specific causes of cub mortality in wild snow leopards (Johansson et al. 2020; Pålsson 2022). The potential threats are largely inferred from studies on other large solitary carnivores and include predation, exposure, and disturbance by humans (Elowe & Dodge 1989; Laurenson 1994b; Yosef et al. 2024). These are likely risks, but direct observations are rare due to the species' elusive nature and the inaccessibility of denning sites. Understanding maternal snow leopard's behaviour and what limits she faces in raising her young is an important part of snow leopard conservation biology. Population growth in felids with similar reproductive rates as the snow leopard has shown most dependent on survival of adult females (Thomas McCarthy & David Mallon 2016). Studies on the reproductive behaviours and costs of female snow leopards are therefore crucial for our ecological understanding of the species.

Snow leopards are enigmatic animals and keep a low profile making them very difficult to observe and study, which is not made easier by the remote landscape they inhabit. With a low body, long tail for balance and a highly camouflaging thick fur for cold temperatures and open areas, the snow leopard is well suited for the mountainous highlands it lives in (Fox et al. 2024a). Thus, studies have been performed mainly with methods using radio- and satellite-telemetry (Fox et al. 2024a). Global Positioning System (GPS) technology has proven to be effective in a number of snow leopard studies but also has its limitations (Fox et al. 2024a). Particularly when observing female movement during denning because the den's rocky walls will often obscure any signals from the collar (Pålsson 2022). Johansson et al. (2022) found however that GPS collars equipped with dual-axis accelerometers provided sufficient data to analyse snow leopard's activity rate. By recording motion sampling at a specific time and point, accelerometer motion data was found to be an effective and more detailed indicator of snow leopards' general activity patterns compared to GPS data.

This is the first empirical activity pattern study of female snow leopards with cubs using accelerometer motion data and will add to the understanding of female snow leopard behaviour during this critical period. Female snow leopards have a high reproductive investment and thus likely show adjustments to their activity and behaviour as is seen in other felids. Female leopards (*Panthera pardus*) show a sensitivity to their offspring's needs and seem to adjust accordingly, which may include adjusting their activity patterns (Balme 2017). Breeding females of the Iriomote cat (*Prionailurus bangalensis iriomotensis*) exhibits a unique midday activity peak during the nursing period, likely due to short and frequent trips between the den and hunting grounds (Schmidt et al. 2009). The female Eurasian lynx (*Lynx lynx*) with kittens show more evenly distributed activity across the day and night and are active twice as long per day as non-reproducing females, especially during the first four months after birth (May-August) (Schmidt 1999).

The aim of the current study is to examine how female snow leopards with dependent young adjust their daily activity patterns, and to evaluate how these patterns reflect the behavioural and energetic demands of reproduction. To do this we will quantify daily and seasonal patterns of female snow leopards with dependent young using accelerometer data. Specifically, we will compare the timing (day, dusk, night and dawn) and intensity of activity during different periods in relation to cub rearing. We will subsequently interpret behavioural activity changes between periods as potential strategies to balance cub care, hunting efficiency and thermoregulation. This will provide previously unobserved baseline activity patterns for breeding female snow leopards and suggest recommendations for conservation of the snow leopard, by highlighting when reproductive female snow leopards are particularly sensitive to disturbance or habitat use constraints. We will focus on the following questions:

- Do female snow leopards with dependent young exhibit different daily activity patterns compared to adult female snow leopards without cubs and how does their activity level and proportion of time active change throughout the 24-hour cycle?
- How does the activity pattern of these breeding females vary during different developmental stages of their cubs?
- What are the potential conservation implications of these activity patterns?

2. Method

2.1 Study Area

The snow leopards were studied in South Mongolia, in the Tost Mountains (43°N, 100°E) of the Gobi Desert (Fig. 1). With altitudes ranging from 1600 to 2500 meters above sea level the mountain range consists of rocky and rugged terrain with a dry and windy climate. The study area is 1700 km² in size and is characterised by wide valleys, large crevasses and ravines crossing the mountains, which are separated by 40 km of steppe to the closest neighbouring mountain range. With a sparse vegetation that consists of shrubs (*Amygdalus mongolica, Caragana leucophlaea* and *Eurotia ceratoides*) and grasses (*Stipa spp*.) and annual temperatures ranging from -27°C to 33°C, Tost mountains provide a rugged and open habitat. Gurvantes is a village located approximately 45 km east of the study area's base camp. Although it lies at a lower elevation and is consistently warmer than the Tost Mountains, the overall temperature trends remain comparable. During the snow leopard birthing months of April, May, and June, average daily minimum and maximum temperatures in Gurvantes increase steadily: approximately 3.2 °C and 13.0 °C in April, 9.1 °C and 19.1 °C in May, and 15.1 °C and 24.6 °C in June. The Tost Mountains has been estimated since 2009 of having a population of 10-14 adult snow leopards (Sharma et al. 2014).

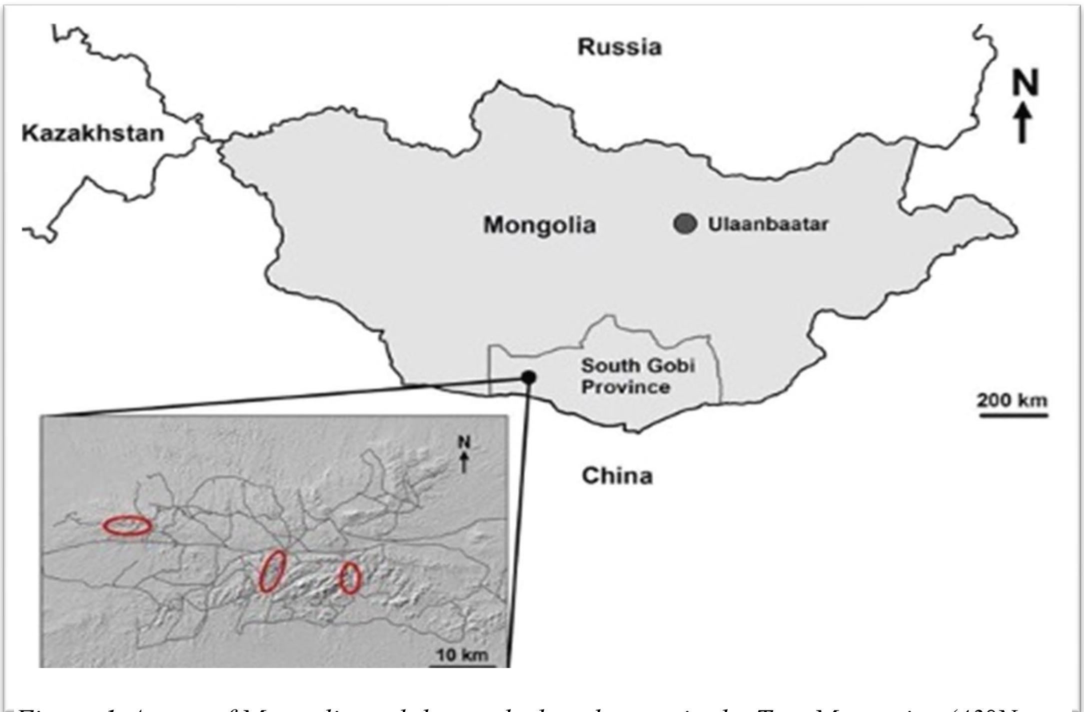

Figure 1:A map of Mongolia and the marked study area in the Tost Mountains (43°N, 100°E) of the Gobi Desert. The inset is a satellite image of Tost Mountains, the trap areas where the female snow leopards were caught are shown with red circles, grey lines show car tracks and motorbike trails.

Other species that inhabit the area are the lynx (*Lynx lynx*), wolf (*Canis lupus*), red fox (*Vulpes vulpes*) and the snow leopard's main prey, the Siberian ibex (*Capra sibirica*) and Argali sheep (*Ovis ammon*). Domestic livestock such as goats (*Capra hircus*) and sheep (*Ovis areas*) roam the area herded by approximately 90 semi-nomadic herder families (for more information on the study area see (Johansson 2017; Johansson et al. 2022).

2.2 Reproduction

The snow leopards' mating season occurs between January and March and the offspring are born between April and June (Johansson et al. 2020). The cubs are birthed most commonly in a secure cave or crevice and the female will give birth to an average of two cubs but it can range from 1 up to possibly 5 cubs (Sunquist & Sunquist 2002). Snow leopard cubs are dependent on their mother until ~20-22 months of age after which they become completely independent (Johansson et al. 2020). During the first week of life (Fig. 2), the cubs are blind, unable to walk nor thermoregulate properly; it has been observed that mothering females will spend the majority of their time with their newborn cubs (Sunquist & Sunquist 2002; Pålsson 2022). Cubs in captivity have been known to start eating solid foods and walk upright at 5 weeks of age (Sunquist & Sunquist 2002). Once the cubs can digest solid food, the female will likely have to increase the predation rate to keep up with the cubs food intake (Olson et al. 2011) and perhaps for the female's nursing energy needs (Schmidt et al. 2009). The birthing den is abandoned after 1-2 months and the cubs begin to travel with their mother (Pålsson 2022). During this time, the female snow leopard will hide her young while she is hunting, often at a previous kill site and then return and travel with her cubs to the new kill site (Pålsson 2022); Snow Leopard Trust, unpublished data). At 10 weeks the cubs are weaned and from 5-6 months of age they begin continuously travelling with their mother (Sunquist & Sunquist 2002; Pålsson 2022).

A snow leopard's home range is vast with adult male's estimated at 207 km^2 (±63) and female's estimated at 124 km^2 (±41) (Johansson et al. 2016). Normally adult female seasonal home range sizes are found to stay relatively stable due to consistent prey availability (Johansson et al. 2018); however, during early post-denning a female's home range is significantly smaller and slowly increases in size in relation to her cubs development (Pålsson 2022). This reflects restricted movement due to cub dependency and suggesting that this restriction eases as cubs become more mobile and hunting increases (Pålsson 2022).

Figure 2: 3-week old snow leopard cubs in den (South Mongolia, Tost Mountains). Photo by: Snow Leopard Trust

2.3 Data Collection

Activity data from 9 female snow leopards (Table 1), during 10 breeding events, are the focus of the study. These data were collected from the same type of GPS-collars used by Johansson et al. (2022) in their study that compared activity patterns of snow leopard males and females (without young cubs) across seasons. The snow leopards were captured between 2009 and 2023 using foot snares that were set up at marking sites and further sedated and immobilised by a mixture of tiletamine-zolazepam and medetomidine (Johansson et al. 2013). The captured individuals were fitted with Vectronic GPS-plus collars (Vectronic Aerospace, Gmbh, Berlin, Germany) that recorded GPS-locations every five hours and equipped with dual-axis accelerometers. The accelerometers measure movement four times per second, logging a mean value between 0 (immobile) and 255 (extremely active) every five minutes. The GPS-collars have an inbuilt drop-off mechanism, programmed to release the collar after a pre-defined period of time (12-22 months). The activity data from the accelerometers was collected once the collars were retrieved and yielded 1.627 million observations for the 9 breeding female snow leopards. Data were downloaded either after the collars had fallen off, during a recapture or after a snow leopard died.

2.4 Data Analysis

For activity, recorded times for each accelerometer observation were transformed into ‘sun time’ from clock time to calibrate activity in relation to comparable day length periods during the study (Nouvellet et al. 2012). This is because animals with diurnal variation in activity patterns change their patterns in relation to the position of the sun (especially sunrise, sunset and when the sun is at its highest point in the sky) rather than using our concept of time. To calibrate clock time to sun time, we used the same methods described in Johansson et al. (2022): i.e. the sunTime() function from the ‘overlap’ package in (Ridout & Linkie 2009). From this we used the function developed in Johansson et al. (2022) that creates daily activity density curves. This means that the y-axis is scaled so different activity density curves can be compared between different time periods. For this we describe and compare the mean daily activity patterns for the 9 female snow leopards during the following time periods: (1) 2-4 weeks before parturition, (2) 0-2 weeks before parturition, (3) each of the first 8 weeks from time of parturition, (4) the early post-denning phase (2-3 months after parturition), and (5) the late post-denning phase (5 to 6 months after parturition). In addition, we compare these changing activity patterns around birth to the same females at the same time of the year for the year prior to birth (i.e. female has no dependent cubs) and in the year after birth (when the female has 1-year-old cubs). These comparisons include the first 5 months after parturition and 12 to 17 months after parturition to examine the impact of young cubs on female activity.

We also used Generalised Additive Models (GAMs) to explore how the proportion of time female snow leopards were active varied across the reproductive stages, with a specific focus on key daily time periods: dawn, solar noon, dusk, and midnight. Activity was treated as a binary response variable, each 5-minute accelerometer sample was classified as either ‘active’ or ‘inactive’ using a threshold value of 27, based on the mean activity score in that 5-minute interval. This thresholding allowed us to model the probability of being active during different time periods as a ‘yes/no’ outcome across time. The GAM approach provided a flexible means of capturing non-linear changes in activity patterns over the reproductive stages, highlighting shifts in temporal behaviour as cubs developed. This analysis closely follows the methodological framework described by Johansson et al. (2022) in their study of seasonal activity variation in snow leopards, but here we applied it specifically to assess changes in diurnal behaviour in female snow leopards during cub rearing.

2.5 Study Limitations

This study is subject to several limitations that should be considered when interpreting the results. First, the data collection occurred over multiple years, during which environmental conditions such as prey availability, snow cover, and weather may have varied and affected the quality of cub-rearing and general activity patterns. Consequently, comparisons across reproductive stages may be influenced by interannual variation unrelated to reproductive status alone. Additionally, not all females in the dataset were represented in each reproductive category (i.e. for the comparisons between the pre-birth, birth and post-birth years), which may introduce individual biases and result in non-uniform patterns across groups. Another limitation lies in the data type itself, while accelerometer data provides a qualitative proxy for snow leopard activity, it does not represent actual behavioural states. The accelerometer value reflects relative movement but has no inherent behavioural meaning (Johansson et al. 2022). As such, it is not possible to determine from the data whether a female was walking, hunting, feeding cubs, or engaged in other forms of activity. Furthermore, although accelerometer data complements GPS data, the two are not directly equivalent, and some behavioural interpretations may vary. These constraints underscore the importance of cautious interpretation when linking activity patterns.

Table 1: Snow Leopard female's ID number, date of collaring, date of collar falling off and birth date of cubs.

ID	Collar on	Collar off	Cubs Born
F4	2010-10-18	2011-10-15	2011-05-01
F5	2011-04-17	2012-08-09	2012-05-31
F6	2011-04-23	2012-10-19	2012-06-01
F8a	2012-05-05	2013-10-19	2012-06-23
F7	2012-04-27	2013-09-10	2013-06-07
F10	2017-05-04	2019-01-01	2017-06-28
F8b	2017-11-04	2019-07-04	2019-04-29
F14	2019-10-25	2021-07-15	2020-06-20
F12	2022-05-01	2024-02-26	2023-05-21
F15	2024-02-26	2024-06-18	2024-04-30

3. Results

3.1 Motion activity patterns during the 24-hr cycle

3.1.1 Pre-parturition.

Patterns of motion activity for female snow leopards in the month prior to giving birth displayed a progressive decline from a bimodal activity pattern with obvious peaks at around dawn and dusk, to a narrowing of these main movement-periods and a decrease in the overall level of activity (Fig. 3). Four weeks before parturition showed distinct activity peaks during dusk and dawn and a low activity pattern during the daytime; two weeks before parturition the peaks attenuated and the low activity pattern continued to trend during the daytime (Fig. 3a). The week of parturition (week 0) dawn activity was greatly reduced (Fig. 3b): with the dawn activity peak completely absent and the lowest point of activity at approximately ~8-9am and a steady increase of activity during the later half of the day leading to dusk. Female snow leopards during the first week of birth appeared to show a small midday activity peak and a remaining dominant evening peak that is sharper and has a more isolated expression compared to the weeks before parturition (Fig. 3 and 4).

3.1.2 Denning

The first 8 weeks following parturition (representing the 'denning' period) showed female snow leopard activity patterns gradually shifting their daily activity from the sudden change in the birth week with no dawn activity peak, to an increasing degree of bimodal activity patterns towards weeks 7 and 8 (Fig. 4). A largely similar pattern could be seen during the first 4 weeks after birth with a relatively low (though gradually rising) broader distribution of activity, with a dominant evening activity peak, relatively higher midday activity, and low morning activity. Lowest point of activity during the first month was at ~8-9am and the highest during dusk (Fig. 4). Hints of a more stable crepuscular pattern appeared during week 4 but a bimodal pattern was not properly distinct until week 5. During the second half of the denning period (weeks 5 to 8), times of activity became more distinguished with dusk and dawn peaks more defined (Fig. 4): with daytime activity decreasing, though midday activity peaks were still prominent during weeks 6 and 8. By week 8, the mother's activity pattern more closely resembled that of non-reproducing females (Fig. 5b and 6a blue dotted line).

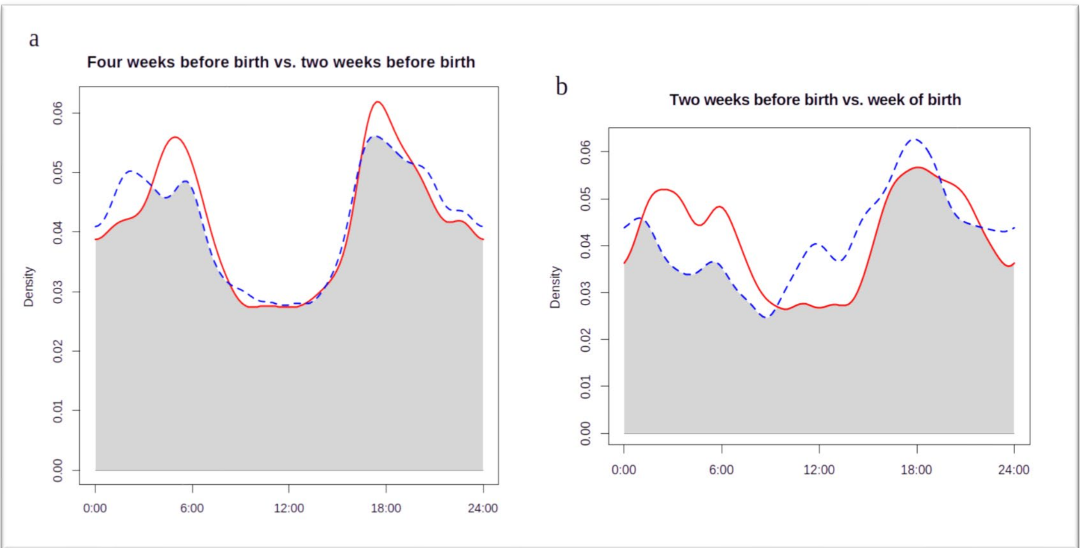

Figure 3: Figure 1a and b. Relative activity level over the 24-h cycle for female snow leopards during the final weeks leading up to parturition. Left plot (a) compares the proportion of activity from 4 weeks (red solid line) and 2 weeks (blue dashed line) before parturition. This shows that the bimodal activity pattern is relatively consistent during this time. Right plot (b) compares 2 weeks before parturition (red solid line) and the birth week (blue dashed line). This shows the bimodal pattern changing during the birth week to much lower activity in the morning, and higher later during the day and evening. Y-axis shows relative measures of activity as a probability density, calculated from the raw motion data (no absolute meaning of the density values). X-axis showing time of day calibrated according to dawn (06:00) and dusk (18:00). The grey shading shows the common activity between the two comparisons, while the unshaded areas under each line shows where one period deviates from the other.

3.1.3 Post-denning phase

In the early post-denning period (2-3 months after birth) females with cubs have a similar activity pattern to females without cubs during the same time of year: i.e. a crepuscular activity pattern characterized by peaks near dawn and dusk (Fig. 5a). However, females with cubs had a relatively smaller morning activity peak and an elevated evening peak relative to their non-reproducing counterparts. In the late post-denning period (5-6 months after birth) the activity profiles of females with and without cubs was even more similar. Both display a bimodal activity pattern, with differences in peak magnitude less pronounced (Fig. 5).

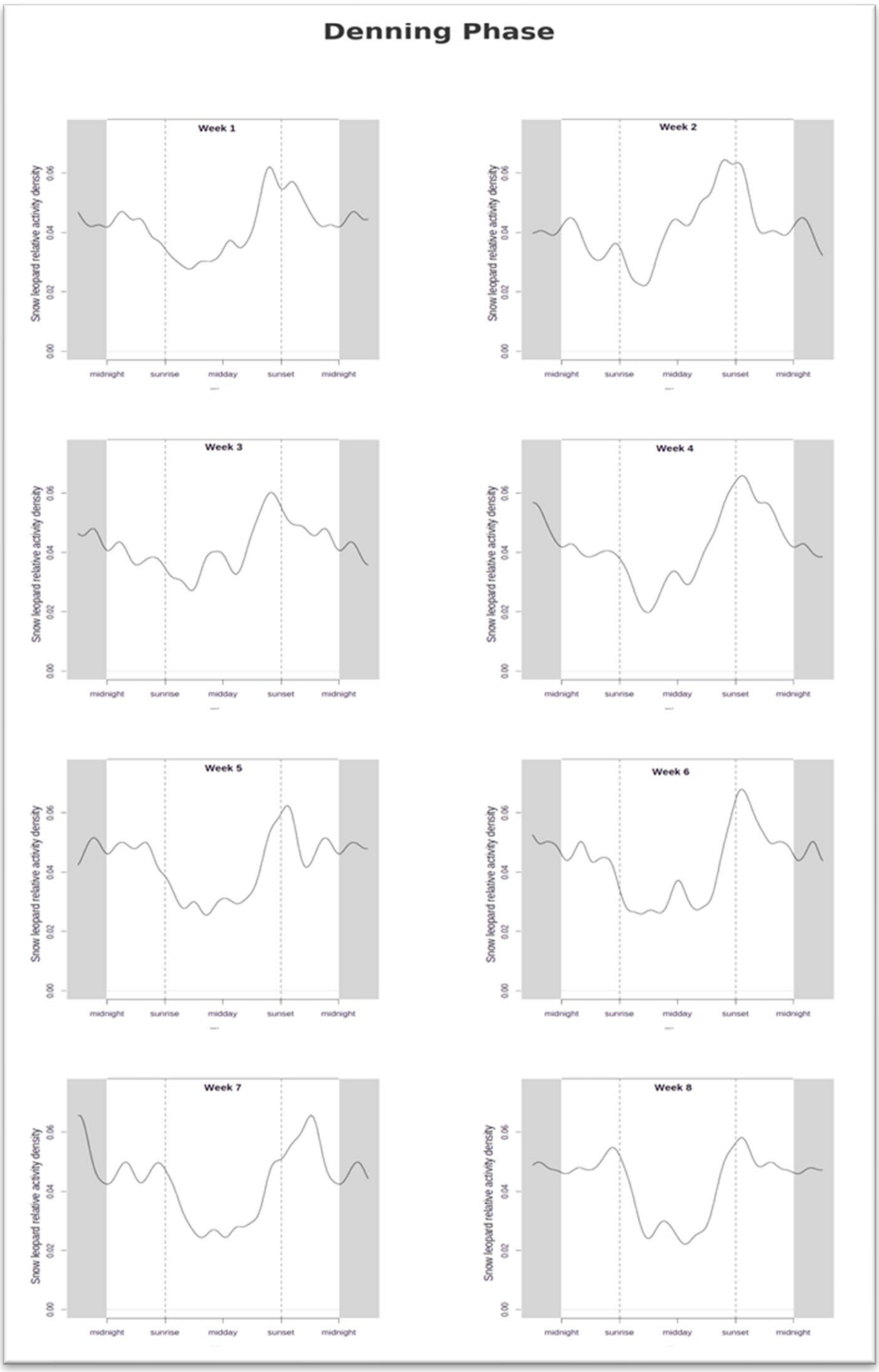

Figure 4: Relative activity density plots for female snow leopards during each of the first 8 weeks following parturition (Denning phase). Each plot represents a one-week interval, plotted over a 24-h period. The x-axis shows the time of all observations as "sun-times". Vertical dashed lines mark the calibrated times of day as sunrise and sunset, with the period between these being daytime (and solar-noon marked as 'midday') and the periods outside of these being night-time (mid-point between sunset and sunrise marked as 'midnight'). The grey area simply shows part of the pattern from the previous day (to the left) or the following day (to the right).

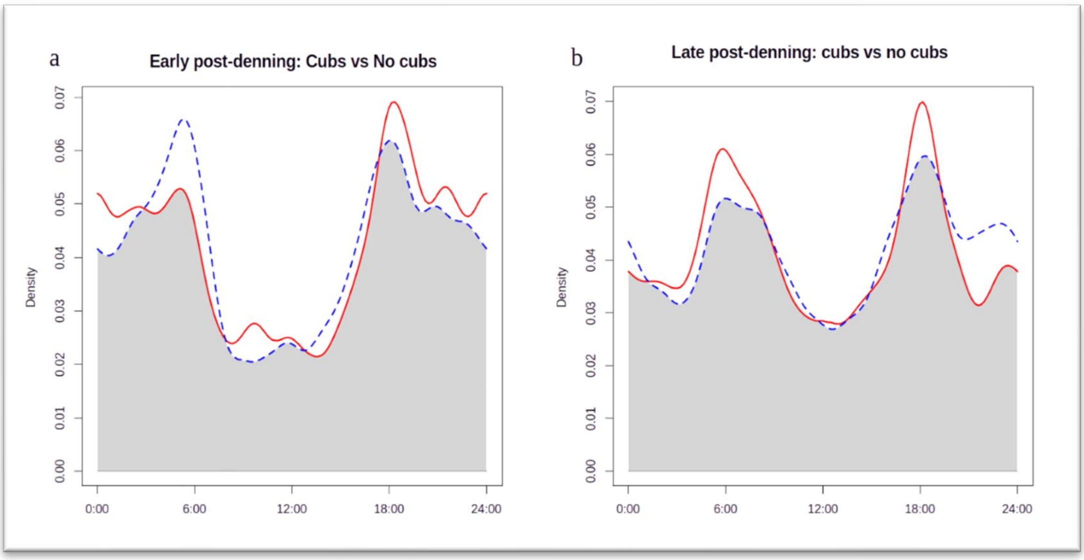

Figure 5: Relative activity level over the 24-h cycle for female snow leopards with cubs (red solid line) and without cubs (blue dotted line) during stages of early and late post-denning phase. Left plot (a) compares the proportion of activity during early stages of post-denning (cubs 2-3 months of age). This shows that the bimodal pattern for females with cubs has a lower and flattened morning peak and a higher evening peak compared to females without cubs. Right plot (b) comparing the late stages of post-denning (cubs 5-6 months of age). This shows that the bimodal pattern for females with cubs has higher morning and evening peaks compared to females without cubs. Y-axis shows relative measures of activity as a probability density, calculated from the raw motion data (no absolute meaning of the density values). X-axis showing time of day calibrated according to dawn (06:00) and dusk (18:00). The grey shading shows the common activity between the two comparisons, while the unshaded areas under each line shows where one period deviates from the other.

3.1.4 Cubs over 12 months of age

Female snow leopards with cubs over 1 year of age showed clear crepuscular activity patterns with high peaks of activity at dusk and dawn (Fig. 6b) Morning activity in mothers with 12-17-month-old cubs is particularly heightened, reaching a sharper and earlier peak than that of their non-reproducing counterparts. Evening activity is similarly intensified, with a steeper rise and higher overall density. In contrast, midday activity remains low in both groups (Fig. 6).

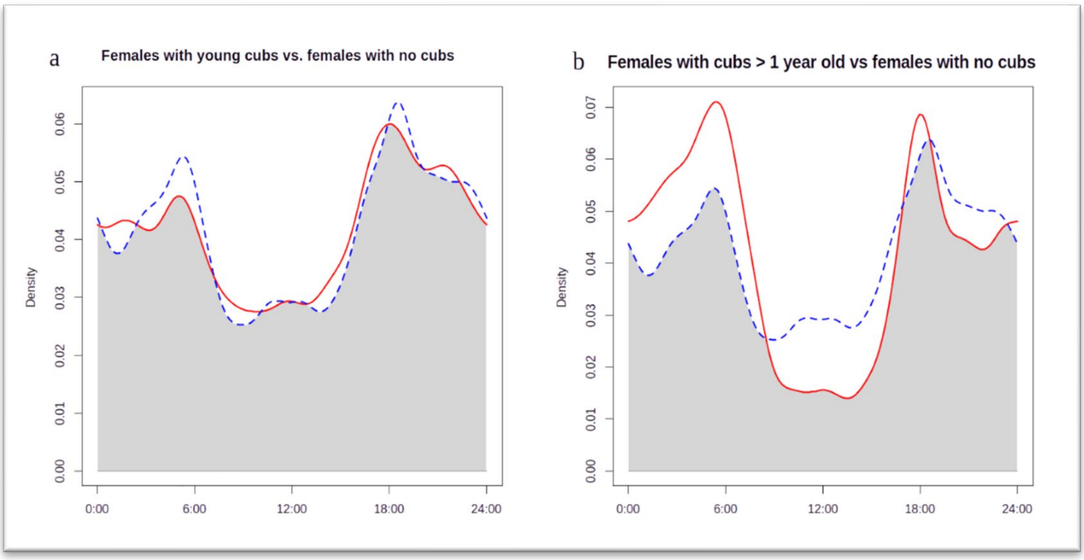

Figure 6: Relative activity levels over the 24-h cycle for female snow leopards with younger and older cubs in comparison to non-reproducing females over a 5 month period (mainly summer). Red solid line represents females with cubs and the blue dotted line represents non-reproducing females. Left plot (a) comparing relative activity for females with cubs under 5 months of age. This shows that the bimodal pattern is relatively consistent but with softer peaks for females with young cubs compared to females without cubs. The right plot (b) comparing relative activity for females with cubs over 1 year of age. This shows that the bimodal pattern has higher and more isolated peaks with lower day activity for females with cubs >1 year old compared to females without cubs. Y-axis shows relative measures of activity as a probability density, calculated from the raw motion data (no absolute meaning of the density values). X-axis showing time of day calibrated according to dawn (06:00) and dusk (18:00). The grey shading shows the common activity between the two comparisons, while the unshaded areas under each line shows where one period deviates from the other.

3.2 Proportion of time active relative to the diurnal period

3.2.1 Dawn

The proportion of time active occurring at dawn varied across reproductive stages. In the birth year, dawn activity showed a marked decline beginning around parturition (week 0), reaching the lowest levels during the early postpartum period (Fig. 7); in contrast, females with cubs over one year of age displayed a steady and notable increase in time active beginning around day 20 postpartum, peaking between days 60 and 80. Non-reproducing females exhibited intermediate values, with the proportion of time active during dawn starting high and slowly decreasing from a few days before the parturition period, though the drop is not as pronounced as in reproductive females (Fig. 7). As females with cubs >1 year old reached a highest point in proportion of dawn activity, non-reproducing females exhibit the opposite with a lowest point of dawn activity during the same period (Fig. 7).

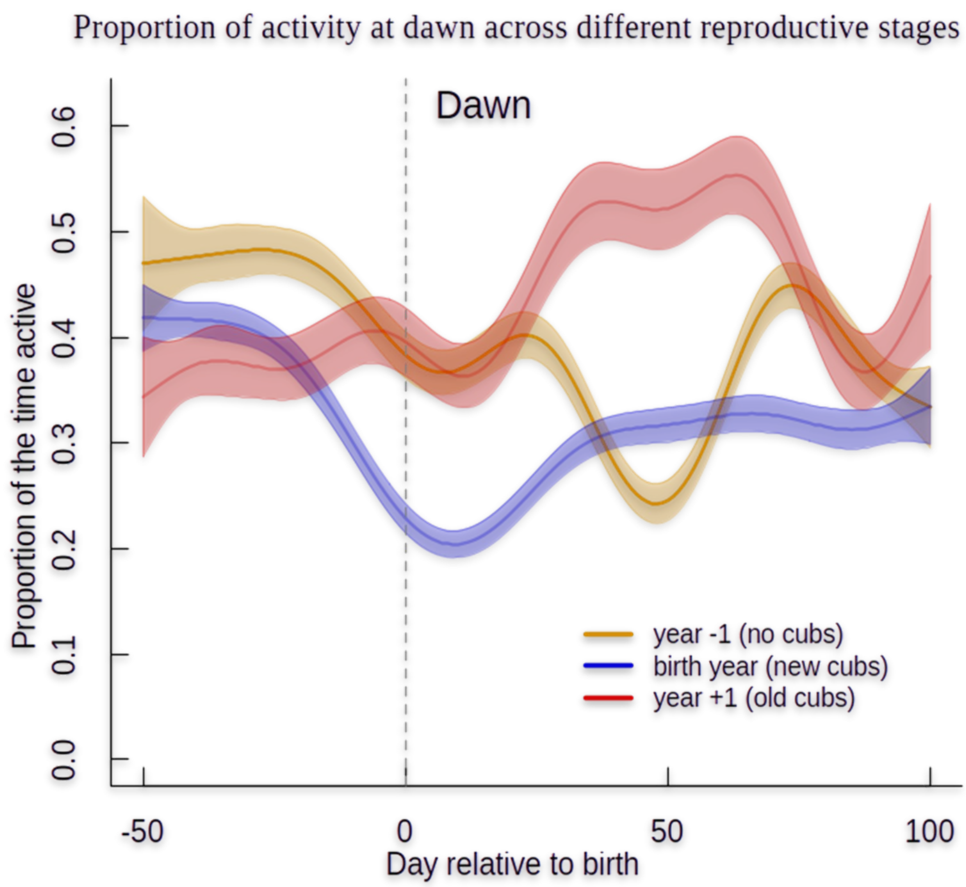

Figure 7: Proportion of time active during dawn hours for female snow leopards across different reproductive stages. The plot illustrates temporal variation in proportion of time active during dawn for non-reproducing females (yellow line), females with young cubs (blue line) and females with older cubs (red line). Activity is modelled using GAMMs and plotted for changes during four time periods: dawn, day, dusk, and night (see figure 6, 7 and 8 for the day, dusk and night periods). The x-axis represents days relative to cub birth (day 0 = birth, vertical dashed line) and matches the birth-relative timeline for comparison with reproductive years. The y-axis shows the proportion of time active (accelerometer >27). Solid lines indicate the mean probability of activity; dashed lines show 95% confidence intervals.

3.2.2 Daytime (Solar Noon)

The proportion of time active during the middle of the daytime period was consistently lower across all reproductive stages, but there were some differences between groups. Females with young cubs in the birth year showed the proportion of time active during the daytime increasing slightly after parturition, reaching a peak at approximately 20 days postpartum and then declining (Fig. 8). In contrast, females with cubs over a year old had the lowest daytime activity overall, with a steep decline during the same year period (cubs 12-14 months old) (Fig. 8).

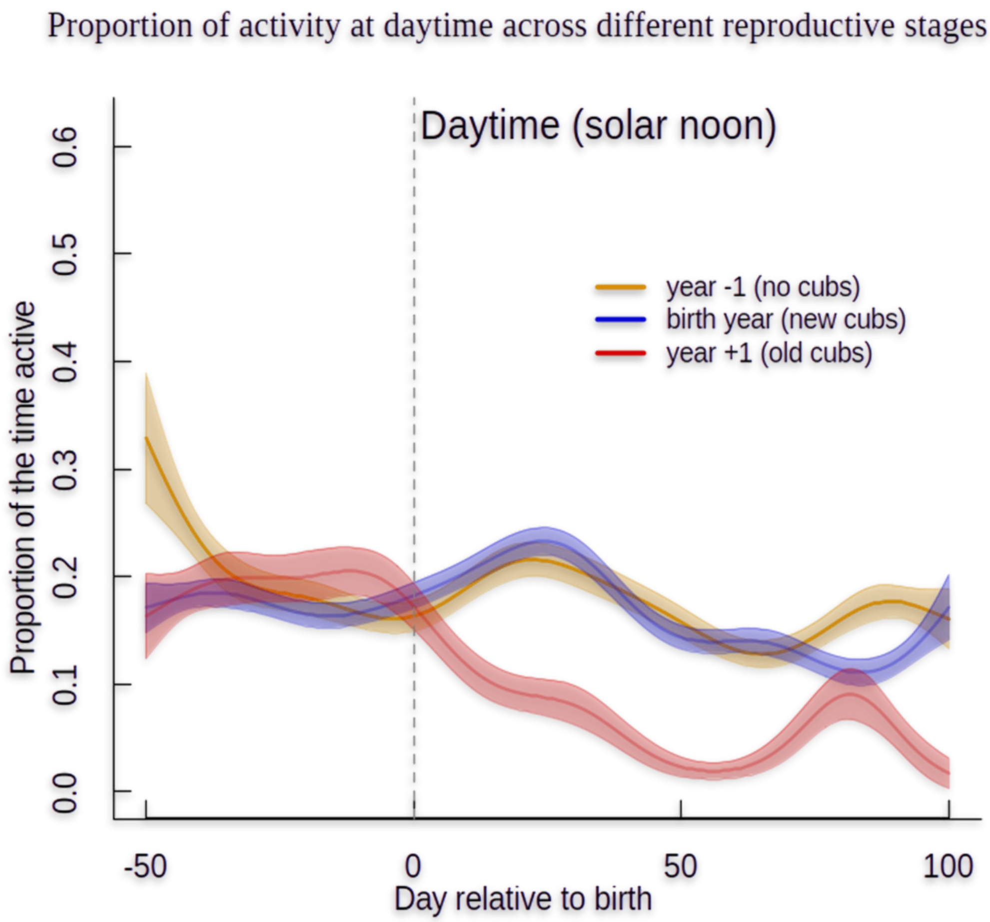

Figure 8: Proportion of time active during daytime (solar noon) hours for female snow leopards across different reproductive stages. The plot illustrates temporal variation in proportion of time active during daytime for non-reproducing females (yellow line), females with young cubs (blue line) and females with older cubs (red line). Activity is modelled using GAMMs and plotted for changes during four time periods: dawn, day, dusk, and night (see figure 5, 7 and 8 for the dawn, dusk and night periods). The x-axis represents days relative to cub birth (day 0 = birth, vertical dashed line) and matches the birth-relative timeline for comparison with reproductive years. The y-axis shows the proportion of time active (accelerometer >27). Solid lines indicate the mean probability of activity; dashed lines show 95% confidence intervals.

3.2.3 Dusk

Dusk was the most stable and dominant activity period across all reproductive stages. Females without cubs showed the highest initial levels of proportion of activity during dusk, which slightly declined around the time of birth (Fig. 9).

Females with newborn cubs maintained a slightly lower dusk activity compared to their non-reproducing year, with a clear dip in activity around parturition and the denning period (Fig. 9). As cubs aged, dusk activity in reproductive females gradually increased again, surpassing non-reproducing female levels by around day 50 (cubs ~14 months old).

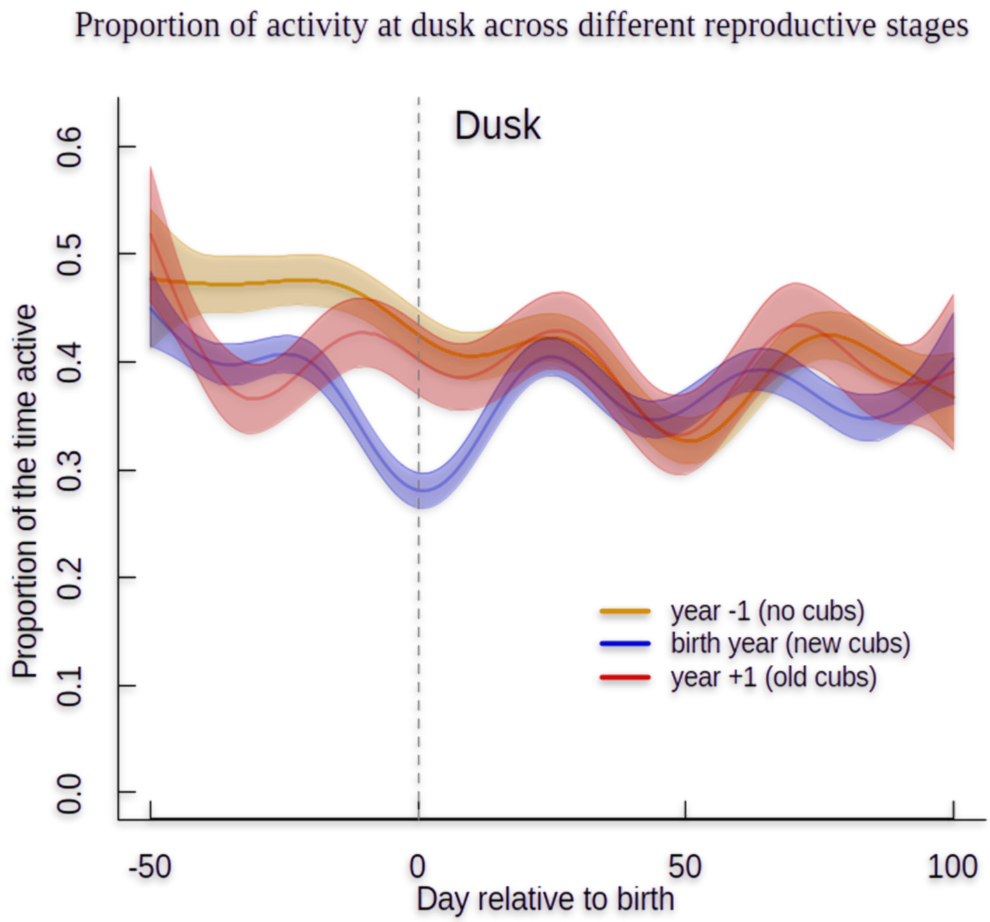

Figure 9: Proportion of time active during dusk hours for female snow leopards across different reproductive stages. The plot illustrates temporal variation in proportion of time active during dusk for non-reproducing females (yellow line), females with young cubs (blue line) and females with older cubs (red line). Activity is modelled using GAMMs and plotted for changes during four time periods: dawn, day, dusk, and night (see figure 5, 6 and 8 for the dawn, daytime and night periods). The x-axis represents days relative to cub birth (day 0 = birth, vertical dashed line) and matches the birth-relative timeline for comparison with reproductive years. The y-axis shows the proportion of time active (accelerometer >27). Solid lines indicate the mean probability of activity; dashed lines show 95% confidence intervals.

3.2.4 Night

Night activity followed a similar trajectory to dawn but was generally lower in magnitude. The proportion of activity during night for females with young cubs decreased slightly around the time of parturition and started to rise again ~1 week after birth, reaching a peak at ~25 days after birth (Fig. 10). In females with cubs older than one year, night activity followed a similar pattern to females with young cubs by increasing gradually, peaking around day 70 (Fig. 10). In contrast, non-reproducing individuals maintained a slightly higher but flatter pattern with minimal fluctuation across the timeframe (Fig. 10).

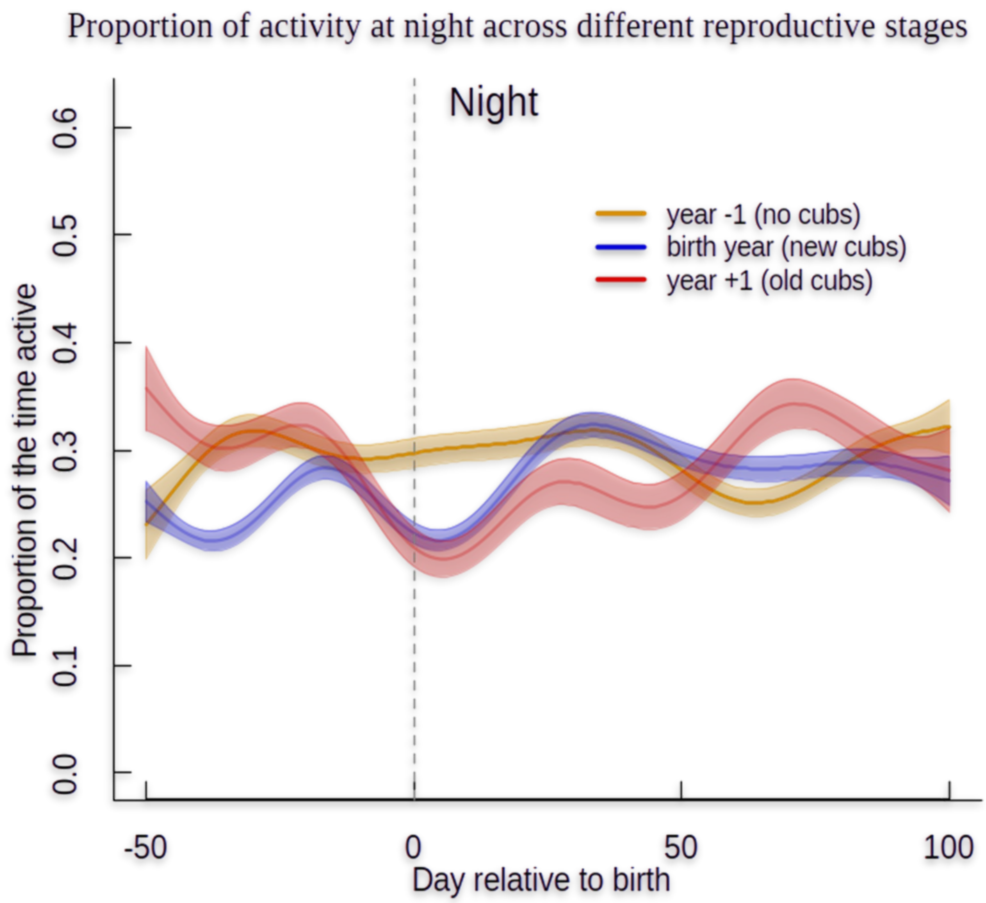

Figure 10: Proportion of time active during night hours for female snow leopards across different reproductive stages. The plot illustrates temporal variation in proportion of time active during night for non-reproducing females (yellow line), females with young cubs (blue line) and females with older cubs (red line). Activity is modelled using GAMMs and plotted for changes during four time periods: dawn, day, dusk, and night (see figure 5, 6 and 7 for the dawn, day and dusk periods). The x-axis represents days relative to cub birth (day 0 = birth, vertical dashed line) and matches the birth-relative timeline for comparison with reproductive years. The y-axis shows the proportion of time active (accelerometer >27). Solid lines indicate the mean probability of activity; dashed lines show 95% confidence intervals.

4. Discussion

4.1 Do female snow leopards with dependent young exhibit distinct daily activity patterns compared to adult female snow leopards without cubs and how does their activity change throughout the 24-hour cycle?

This study demonstrates that reproductive status has a substantial effect on the diel activity patterns of female snow leopards. Using two complementary analytical approaches, overlap analyses and Generalised Additive Models (GAMs), we demonstrate that females with dependent young exhibit distinct temporal activity profiles compared to non-reproducing females. Overlap analysis revealed that reproductive females departed from the consistent crepuscular rhythm seen in non-reproducing individuals, showing a flatter profile with a suppressed dawn peak and a narrowed dusk peak, particularly around parturition. These differences were most evident in the final weeks of pregnancy and the early postpartum period (Fig. 3b and 4), with overall activity declining and crepuscular peaks becoming less defined. During this time, dawn activity was greatly suppressed, a single dusk peak emerged, and a recurring midday peak appeared throughout the denning period. Compared to non-reproducing females, whose activity remained relatively symmetrical across the 24-hour cycle, reproductive females restricted their movement primarily to the evening hours, with markedly lower activity during dawn and the early morning.

Findings show that snow leopards vary in activity patterns seasonally, indicating thermoregulation as an influential factor on daily activity (Johansson et al. 2022). According to Johansson et al. (2022) adult snow leopards tend to shift their activity towards night and dawn during the summer to avoid exertion during periods of heat. This does not seem to be the case for reproductive females who show dominant activity peaks during dusk. The results of this study indicate that denning females are constrained in their ability to make such thermoregulatory adjustments. In the first weeks after parturition, maternal activity was elevated during the warmest parts of the day, this likely reflects a trade-off between minimizing thermal stress and meeting the needs of immobile cubs. Whether this is for feeding, protection, or maintaining warmth in a high-altitude environment can only be speculated so far.

The GAM analysis reinforced these findings by quantifying the proportion of time active during the four key periods of the diel cycle (dawn, solar noon, dusk, and night) and providing a proportional emphasis on activity periods. During early cub-rearing, GAMs showed a marked drop in dawn and night activity, a modest rise in daytime movement, especially during the first two weeks postpartum, and consistently elevated dusk activity. These patterns gradually shifted as the cubs matured. Together, the two methods of analysis provide a more nuanced understanding of behavioural change. The overlap analysis visualises shifts in movement timing and shape, while the GAMs quantify how frequently snow leopards are active during each period.

This reduction in activity and shift in timing likely reflects the physical constraints and behavioural strategies associated with denning and cub protection. By minimizing early morning movement and limiting overall activity, reproductive females may reduce the risk of predation or detection at or near the den site, though the specific threats to snow leopard cubs remain poorly documented. Cubs are typically born during the seasonal transition from spring to summer, (April-June) when temperatures can still vary substantially between day and night. As shown in the temperature data from Gurvantes, early mornings average as the coldest part of the day. Females may therefore prioritize remaining at the den during these cooler periods to help regulate cub body temperature, particularly in the early weeks after birth when cubs are too small to maintain body heat themselves.

These findings are consistent with previous observations in other solitary felids. For example, in Eurasian lynx, Schmidt (1999) found that females with kittens exhibited longer day activity and more fragmented bouts of activity than non-reproducing individuals, with movement largely constrained to periods that balanced foraging needs and den attendance. Similarly, Iriomote cats showed altered temporal activity during lactation, including midday peaks likely linked to foraging trips between den visits (Schmidt et al. 2009). For snow leopards, Pålsson (2022) reported reduced GPS fix acquisition and tight movement clusters during the first six weeks postpartum, consistent with den site commitment and restricted spatial behaviour. These spatial findings correspond closely to the temporal patterns observed in this study, reinforcing the conclusion that reproductive females adopt a highly modified and risk-averse activity pattern during the early reproductive phase.

Temporal deviations persisted even as cubs matured. Reproductive females showed elevated dusk activity and subdued dawn peaks in the early post-denning phase when the cubs are under 5 months in age (Fig. 5A and 6a). These differences may reflect ongoing energetic demands and the need to coordinate activity with cub movement, even after dens are abandoned.

Collectively, these findings emphasize that reproductive females deviate significantly from the diel rhythms of non-reproducing snow leopards, likely as an adaptive strategy to balance cub care, foraging, and safety during the critical phases of offspring development.

4.2 How does the activity pattern of these mothering females vary during different developmental stages of their cubs?

The diel activity of reproductive female snow leopards differs markedly from that of non-reproducing females, with the degree of difference varying across the period of cub dependency, indicating that the developmental stage of the cubs strongly influences maternal activity. The varied differences reflect the mother's ongoing reproductive investment and energetic demands that evolve and subside throughout the rate of her cub's dependency.

The time leading up to the parturition the female's activity became lower and more restricted (Fig. 3), most likely reflecting the energetic demand of pregnancy and the need to be close to a suitable denning area. The proportion of time active leading up to parturition was declining during dusk, dawn and night, while the portion of time active during day was increasing. Immediately after parturition, maternal activity was heavily constrained. During the first 3 weeks, reproductive females exhibited minimal overall movement (lowest point at ~8-9am), with flattened diel patterns dominated by a narrow dusk peak, reduced dawn activity, and subtle increases in midday movement (Fig. 4). This aligns with the denning period observed by Pålsson (2022), during which females remained near dens to protect neonates. Following parturition, the proportion of time active increased during the dusk and daytime periods, while activity during the night and dawn began to rise approximately two weeks postpartum. As snow leopard cubs open their eyes around seven days after birth, ears after 2 weeks and gain approximately 300–500 grams per week (Sunquist & Sunquist 2002; Fox et al. 2024b), the observed increase in maternal activity during the night and dawn may indicate that females are able to leave the den more frequently and for longer periods as cubs become more developed and resilient.

As cubs continued to develop, the mother's activity pattern gradually shifted. From week 4 onward, a crepuscular rhythm started to re-emerge, with the reappearance of dawn activity (Fig. 4). Midday activity was evident the first 4 weeks and then would disappear every second week up to week 8. By the end of the denning period the diel pattern had stabilized into a more typical bimodal form, which coincides with cub milestones. This pattern increasingly resembled that of non-reproducing females, suggesting that the mother's movement becomes progressively less constrained as cubs grow, begin consuming solid food, and are more mobile or left for longer periods. These behavioural adjustments are consistent with lactation-based energetic demands and the need to provision for growing offspring (Sunquist & Sunquist 2002; Olson et al. 2011). According to Pålsson (2022), some females may abandon the den as early as one month postpartum, a behavioural shift that likely influences activity patterns. The emergence of a distinct crepuscular rhythm by week five, coinciding with the developmental milestone of cubs beginning to walk and digest solid food (Sunquist & Sunquist 2002), suggests that cub mobility and dietary transition are key factors driving the observed shift in maternal activity.

The post-denning phase reflected continued flexibility in maternal activity. In the early post-denning period (2-3 months postpartum), mothers exhibited dusk-dominated activity with a diminished dawn peak, whereas by 5-6 months postpartum, their activity patterns had nearly converged with those of non-reproducing females (Fig. 5). However, slight differences remained, particularly in the amplitude of crepuscular peaks, possibly indicating the energy requirement of feeding more than one mouth or that cubs, though mobile, still required maternal care during hunting and movement. (Gittleman 1986; Pålsson 2022).

As the cubs reached over 12 months in age, maternal activity once again showed signs of adaptation. Diel patterns remained distinctly crepuscular, but with sharper and earlier dawn peaks and more isolated and heightened dusk movement (Fig. 6b). This may reflect a transition toward independence, with mothers either engaging in prolonged travel with their maturing cubs, increasing home range size (Pålsson 2022) or increasing foraging efforts to meet the energetic demands of near adult sized cubs (Olson et al. 2011). Interestingly, by 12-17 months, mothers exhibited higher overall crepuscular activity than non-reproducing females, a contrast to the reduced activity seen earlier in the denning phase, and a sign that cub development is accompanied by a rebound and even elevation in maternal activity.

These behavioural changes are further supported by the GAM analysis, which showed clear differences in the proportion of time spent active across the three reproductive stages. The pre-birth year displayed the most stable crepuscular pattern, with a balanced proportion of activity during dawn and dusk and minimal proportion of daytime activity. During the birth year, the proportion of maternal activity was distributed more broadly across the day, reflecting the constraints of denning and the need for frequent but cautious foraging. In contrast, the year with older cubs was characterised by a sharp reduction in proportion of daytime activity and a marked increase in dawn and dusk, possibly reflecting more deliberate, concealed movement while travelling with dependent cubs. These patterns suggest that as cubs develop, mothers shift from broad, flexible activity to a more refined schedule that maximises efficiency while minimising risk.

4.3 What are the potential conservation implications of these activity patterns?

4.3.1 Heightened vulnerability during denning

The activity patterns observed in this study provide critical insights into the behavioural ecology of reproductive female snow leopards and carry important implications for conservation planning. Maternal females exhibit distinct temporal shifts in activity that align closely with cub development, revealing periods of heightened vulnerability during which disturbance may have disproportionately negative impacts on both the mother and her offspring.

The denning phase represents a particularly sensitive period. During this time, females exhibited suppressed dawn activity, reduced overall movement, and a dominant but narrow dusk activity peak. These patterns are consistent with restricted movement around birth dens, as cubs are immobile and require constant care. Similar patterns have been observed in Canada lynx (Olson et al. 2011), Iriomote cats (Schmidt et al. 2009), and leopards (Balme et al. 2017), where reproductive females reduced mobility and modified their temporal activity in response to the demands of offspring protection and provisioning. Such behaviour suggests a strategy of minimizing exposure to potential threats, while maintaining essential foraging. While direct observations of threats to snow leopard cubs are rare due to the species' elusive nature, studies on comparable solitary felids, such as Iriomote cats and Canada lynx (Schmidt et al. 2009; Olson et al. 2011), suggest that maternal behaviours like den relocation and altered activity patterns are responses to environmental risks, including predation and energetic constraints. These inferred vulnerabilities support the consideration of potential, albeit largely undocumented, threats to snow leopard cubs during early development.

4.3.2 Implications of climate change

These findings have potential implications under climate change scenarios, where average temperatures are projected to rise and precipitation patterns are expected to become more erratic. Denning females, already physiologically stressed by lactation, which requires large amounts of water, may face heightened risk of dehydration if they must remain active in increasingly hot conditions. Panting, the primary cooling mechanism in felids, results in substantial water loss, further increasing dependence on local water sources (Doris & Baker 1981). As climate change may reduce the availability of reliable water, due to less frequent but more intense rainfall events, the suitability of denning sites may become increasingly tied to proximity to permanent water. In areas where natural water holes are likely to dry out, a targeted conservation measure could include the creation or maintenance of artificial water sources near known or potential denning habitats. Such measures would not only support reproductive females but also benefit a wide range of sympatric wildlife in these arid high-altitude ecosystems.

4.3.3 Conflict risk in multi-use landscapes

During the early postpartum period, female snow leopards tend to restrict their movement and remain close to the birth den, often within rugged terrain that may overlap with livestock grazing areas. While they may be in proximity to domestic prey, reproductive females typically avoid targeting livestock, likely to reduce risk to themselves and their dependent young (Johansson et al. 2015). However, their reduced mobility and prolonged den attendance still place them at heightened vulnerability to disturbance and accidental detection, especially in multi-use landscapes. Their limited movement can also reduce detection by camera traps or GPS collars, contributing to underreporting of reproductive females and potentially leading to underestimated breeding rates in population studies (Pålsson 2022).

A particular strength of this study is its focus on cub developmental stages rather than fixed time intervals postpartum. Female snow leopards vary considerably in the timing of den abandonment, with some leaving after just four weeks and others staying for up to eight weeks or more (Pålsson 2022). By aligning activity patterns with observed cub development rather than assuming uniform timing, this study offers a more ecologically grounded understanding of how maternal behaviour adapts to cub needs and how this behaviour translates into conservation vulnerability.

The recognition of temporal activity patterns, such as the dominance of dusk activity during early cub-rearing, can help identify high-risk windows for livestock predation or conflict, informing more targeted mitigation strategies in shared landscapes. This is particularly important given the observation that reproductive females show elevated daytime activity during the denning phase, a deviation from the otherwise crepuscular activity pattern seen in non-reproducing snow leopards and females with older cubs. Johansson et al. (2022) found that domestic goats are active almost exclusively during the day and that snow leopard activity generally does not correlate with that of livestock. This suggests that during the denning period, the female is often the only snow leopard active during daytime hours, potentially increasing her exposure in grazed areas. Although this does not necessarily mean increased livestock predation, the overlap in activity heightens the risk of encounters with herders or domestic animals, and therefore the chance of retaliatory conflict. If a reproductive female is targeted or displaced during this sensitive phase, the survival of her cubs, still entirely dependent, is jeopardized. This creates a conservation concern that goes beyond individual loss and has implications for population viability, given the species low reproductive rates and extended maternal investment.

4.3.4 Improving monitoring and research ethics

These findings also have important implications for research methodology and ethical practice. Understanding the timing and structure of maternal movement enables researchers to design monitoring efforts, such as camera trap placement or collaring, with greater sensitivity to the behavioural constraints of reproductive females. In doing so, conservationists can minimize unintended disturbance during critical maternal phases and promote ethical standards in wildlife research.

As cubs develop and maternal activity increases, particularly during post-denning and subadult phases, female snow leopards transition back toward a more typical crepuscular pattern. This shift suggests increased foraging demands and a reduced need to remain close to cubs, which may also expand their spatial exposure. Because this behavioural transition occurs gradually over time, it highlights the need for conservation planning to account for the full duration of maternal care, which in snow leopards can extend up to 20-22 months (Johansson et al. 2020).

Informed by these behavioural patterns, conservation strategies must be both temporally and spatially sensitive. Livestock herding and other human activities should be minimized around dusk and in known maternal snow leopard ranges, particularly during denning and early cub-rearing phases. Moreover, protected areas must not only cover sufficient habitat size (Johansson et al. 2016) but also maintain functional connectivity that allows females to access safe denning and foraging areas throughout the reproductive cycle. As other studies have noted (Horion et al. 2024; Jędrzejewski et al. 2021), understanding when and how reproductive carnivores use space is essential to reducing conflict and targeting conservation resources effectively.

5. Conclusion

This study offers a more detailed understanding of female snow leopard behaviour by combining complementary analytical approaches, activity overlap analysis and Generalised Additive Models (GAMs), to examine how maternal activity shifts in response to cub dependency. The results show that reproductive status significantly shapes diel activity patterns, with pronounced adjustments during denning, followed by gradual transitions back toward pre-reproductive activity rhythms. As cubs grow, maternal activity not only returns to a crepuscular pattern but is also elevated to meet the rising energetic demands of provisioning for dependent young.

These findings build upon earlier studies documenting denning behaviour, reproductive investment, and general activity in snow leopards, and extend them by offering a continuous, fine-scale view of how activity changes throughout the reproductive cycle. Viewing activity through a developmental lens reveals how maternal behaviour shifts over time in response to cub growth and caregiving constraints. By integrating timing, intensity, and context of movement, this work contributes to a growing behavioural framework that identifies key periods of maternal vulnerability, particularly when movement is most restricted and cubs are most dependent. These behavioural constraints may be exacerbated by climate change, which is projected to increase thermal stress and reduce access to vital water sources during the denning period.

Such vulnerability arises not only from the energetic demands of reproduction but also from an increased risk of disturbance in shared-use landscapes. Recognising these temporal shifts in activity provides essential context for both carnivore ecology and conservation. Incorporating maternal behaviour into conservation planning, whether in conflict mitigation, land-use decisions, or monitoring design, can help reduce risks to females and improve cub survival. Ultimately, behavioural ecology offers practical tools to enhance conservation strategies, particularly in human-dominated environments where reproductive success is easily disrupted.

Future studies should continue to build on this framework by incorporating spatial data, direct behavioural observations where possible, and expanding the number of known reproductive events. A deeper understanding of how maternal activity varies across individuals, environments, and seasons will further strengthen efforts to protect breeding females and their cubs. By better understanding the behavioural ecology of maternal snow leopards, we can improve conservation efforts that ensure both individual survival and population-level reproductive success.

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