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Changing Climates, Changing Behaviors: A Behavioral Lens on the Snow Leopard (*Panthera uncia*)

Zmiany klimatu a zmiany zachowań – perspektywa behawioralna w badaniach nad irbisem śnieżnym (*Panthera uncia*)

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Abstract: Climate change is rapidly reshaping high-altitude mountain ecosystems, with far-reaching consequences for the endangered snow leopard (*Panthera uncia*). Rising temperatures, altered snow cover, and shifting precipitation patterns are contracting cryospheric habitats and restructuring prey distributions, forcing snow leopards to modify how and where they move, hunt, and interact with other species and people. This narrative review synthesises peer-reviewed studies, conservation reports, and climate assessments (2000–2024) from across the Hindu Kush–Himalaya and adjacent ranges to examine climate-linked changes in snow leopard behavioural ecology. We summarise evidence for habitat contraction and upslope shifts, altered movement and home range, changes in predation and scavenging behaviour, enhanced human–snow leopard interactions, and emerging interspecific competition with other large carnivores. We then explore the implications of these behavioural responses for conservation planning, highlighting how climate-driven changes in activity patterns, space use, and conflict risk challenge static protected area models and conventional conflict-mitigation approaches. On this basis, we outline key elements of a behaviour-informed conservation agenda, including dynamic protected areas, climate-smart corridors and livelihoods, systematic integration of behavioural monitoring, and community-based governance embedded in international initiatives such as GSLEP. We argue that snow leopard behaviour offers a sensitive indicator of climate-induced ecological stress and should be central to adaptive, climate-aware management of vulnerable high-mountain ecosystems.

Keywords: snow leopard, behavioural ecology, climate change, high-altitude ecosystems, mountain biodiversity, human–wildlife conflict, SDG 13 – Climate Action, SDG 15 – Life on Land

Streszczenie: Zmiany klimatyczne powodują szybkie przekształcenia w wysokogórskich ekosystemach, wywołując daleko idące konsekwencje dla zagrożonego wyginięciem irbisa śnieżnego (*Panthera uncia*). Wzrost temperatury, zmiany w pokrywie śnieżnej oraz zmieniające się wzorce opadów prowadzą do kurczenia się siedlisk kriosferycznych i zmian w rozmieszczeniu gatunków ofiar irbisa. W rezultacie irbisy śnieżne są zmuszone do modyfikowania miejsc bytowania, strategii polowania oraz sposobów interakcji z innymi gatunkami i z ludźmi. Niniejszy przegląd literatury obejmuje recenzowane publikacje naukowe oraz raporty z zakresu ochrony przyrody i ocen klimatycznych z lat 2000–2024, dotyczące regionu Hindukuszu, Himalajów i przyległych pasm górskich. Celem opracowania jest analiza zmian w ekologii behawioralnej irbisa związanych z postępującymi zmianami klimatycznymi. Podsumowujemy dowody wskazujące na kurczenie się siedlisk i ich przesuwanie ku wyższym partiom gór, zmiany w przemieszczaniu się i lokalizacji terenów łowieckich irbisa,

modyfikacje zachowań związanych z polowaniem i padlinożerstwem, nasilenie kontaktów z ludźmi oraz pojawiającą się konkurencję międzygatunkową z innymi dużymi drapieżnikami. Następnie analizujemy konsekwencje tych reakcji behawioralnych dla planowania działań ochronnych. Pokazujemy zmiany aktywności zwierząt, użytkowania siedlisk oraz ryzyka konfliktów, wywołane zmianami klimatu, które stanowią wyzwanie dla statycznych modeli obszarów chronionych i konwencjonalnych metod łagodzenia konfliktów człowiek – dzika przyroda. Na tej podstawie przedstawiamy kluczowe elementy programu ochrony przyrody uwzględniającego zachowania gatunku, w tym dynamiczne obszary chronione, korytarze ekologiczne oraz źródła utrzymania przyjazne dla klimatu, systemową integrację monitoringu behawioralnego oraz zarządzanie oparte na społecznościach lokalnych, osadzone w międzynarodowych inicjatywach takich jak Global Snow Leopard and Ecosystem Protection Program (GSLEP). Wskazujemy, że zachowanie irbisa śnieżnego stanowi czuły wskaźnik ekologicznych skutków zmian klimatycznych i powinno odgrywać kluczową rolę w adaptacyjnym, uwzględniającym zmiany klimatu zarządzaniu wrażliwymi ekosystemami wysokogórskimi.

Słowa kluczowe: Irbis śnieżny, ekologia behawioralna, zmiany klimatu, ekosystemy wysokogórskie, bioróżnorodność górska, konflikt człowiek–dzika przyroda, SDG 13 – działania w dziedzinie klimatu, SDG 15 – życie na lądzie

Introduction

The snow leopard (*Panthera uncia*), a top predator in the high-altitude ecosystems of Central and South Asia, faces severe threats due to climatic and ecological changes (Din 2023). This cold-reliant top predator remains elusive but is increasingly susceptible to climate disruptions. Snow leopards are sensitive to changes in temperature, precipitation and snow cover, all of which are being altered by climate change. Currently, snow leopard habitats are undergoing rapid alterations as mountain areas are warming nearly twice as fast as the global average, which affects their behaviour and survival (Farrington and Li 2024).

Snow leopards demonstrate remarkable adaptability and resilience despite existing ecological challenges (Zhang et al. 2025). While all species adapt to opposing forces in diverse ways, and an organism's behaviour is one of the first biological traits to respond to environmental stress (Tuomainen and Candolin 2011). Increases in movement range, alteration of hunting schedules, adaptation to anthropogenic landscapes, and heightened inter-specific engagements all attest to the resilience and adaptability of snow leopard to changing conditions, including those from climate changes (Ma et al. 2024).

Despite its status as a conservation icon, essential knowledge gaps remain about how climate change influences snow leopard behavioural ecology. Most studies have focused on habitat modelling or population estimates, with little attention paid to behavioural plasticity as a response to climate change (Forrest 2012; Li 2016). This review aims to provide an organized synthesis of behavioural evidence associated with climate-induced ecological stressors.

1. Research Methodology

This review follows a qualitative narrative synthesis approach. Peer-reviewed journal articles, organizational reports e.g., WWF, Snow Leopard Trust, and climate change assessments from 2000–2024 were accessed via Web of Science, ScienceDirect, Google Scholar, and Scopus. Keywords included "snow leopard," "climate change," "behavioural adaptation," "habitat fragmentation," "altitudinal migration," and "human-wildlife conflict." Emphasis was placed on studies focusing on the Hindu Kush Himalaya, Pamirs, and other parts of the snow leopard's distribution range.

2. Results and Discussion

2.1. Habitat Contraction and Altitudinal Shifts

Warming of the Himalaya and surrounding mountain ranges can lead to drastic changes in the structure and availability of suitable habitat for snow leopard (Farrington & Li 2024). The upward shift of treeline, glacier melt, and changes in snow cover are contracting traditional snow leopard habitats. It is estimated that between 20–30% of potential habitat for this species may be lost in parts of its range due to glacial retreat and upward migration of treelines, particularly in the eastern Himalayas (Chettri et al. 2010; Forrest 2012; Li 2016). In Himalayan ecosystems, under climatic warming and treeline ascent, vegetation patterns are also changing, driving prey species such as ibex and markhor further up mountain slopes (Forrest et al. 2012). Snow leopards will follow these prey shifts not because they are bound by thermic limits but out of trophic need. Such seasonal movements will lead predators into prey poor areas, with comparably high hunting costs in terms of energy expenditure and survival (Williams et al. 2020).

Multiple studies suggest that snow leopards already occupy higher elevations in summer, including upward altitudinal movements by male snow leopards in the Mongolian Altai (Rosenbaum et al. 2023) and the predominance of snow leopards' records above 3,800 m in summer versus winter from camera-traps in Nepal's Lapchi Valley (Koju et al. 2023). At higher elevations, snow leopards, in addition to finding reduced opportunities for shelter den sites and cover, will face greater temperature extremes and exposure (Watts, McCarthy, and Namgail 2019). These conditions also likely increase the risk for cubs, particularly in early months, when thermoregulation and security are largely a function of the safety of dens (Chetri et al. 2019).

Predicted rising treelines are also expected to reduce the connectivity of snow leopard habitat patches in the Hindukush-Himalaya region, potentially isolating populations (Riordan et al. 2016), which over decades will likely impede dispersal between populations (Aryal et al. 2016).

With climate change contracting suitable habitat, snow leopards may also come into increased contact within remaining patches, increasing the likelihood of repeated territorial conflict which is both energetically costly and hazardous (Johansson et al. 2016; Li et al. 2016; McCarthy et al. 2016). Other scenarios such as migration into marginal habitats or even declines in the whole population, have also been predicted, showing that overcrowding is not necessarily the only response to habitat loss (Lovari et al. 2013).

Furthermore, the spatial aggregation of populations into ecological "bottlenecks" could limit gene flow between subpopulations. Genetic analyses have previously demonstrated that reduced diversity already occurs in some isolated populations (Janečka et al. 2011), indicating that climate-driven fragmentation could further worsen the risks of genetic isolation. Over extended periods of time, these factors could lead to decreased survival, reduced reproductive success and disruption of social systems, and render snow leopards more vulnerable to stochastic drivers, such as outbreaks of disease or extreme weather.

2.2. Altered Movement and Home Range

GPS-collar studies on snow leopards have demonstrated an expansion in home range size and seasonal movement shifts in snow leopard home ranges (Rosenbaum et al. 2023). These changes may be concurrent with the shifts in prey migration and plant cover growth occurring as a result of climate change. Ibex and Markhor are increasingly driven to follow forage availability to higher elevations (Aryal et al. 2016; Forrest et al. 2012). This indicates that snow leopards will need to modify their hunting ranges accordingly, linking predator behaviour to climate-induced prey migration and plant growth changes. These potential range shifts suggest the behavioural adaptation needed to obtain essential resources under

conditions of changing ecosystem conditions. Some individuals are expanding their home ranges through time; others adapt seasonal movement patterns to adjust to prey migration and habitat change (Li et al. 2021; Rosenbaum et al. 2023). This behaviour plasticity represents an important survival strategy in response to climate change, but with the inevitable consequences of higher energetic demands or human-wildlife conflict. Increased movement also raises the energetic costs of predation, which could decrease survivorship in the long term (SLN 2014). In areas where established corridors are degrading or no longer accessible, snow leopards will be forced to navigate new paths, often at the expense of greater energy expenditure.

What used to be hunting grounds is changing, causing these solitary carnivores to move into human-occupied areas or up mountain slopes (Maletzke 2010). The energetic toll of traversing rugged terrain in search of prey could reduce their hunting success, impact reproductive rates, and even increase mortality (Fox et al. 2024). As a result, long-term survival may hinge on how effectively individuals can adapt to these emerging spatial challenges.

2.3. Climate-Linked Change in Predation Behaviour

Changes in prey availability and distribution due to climate change have an indirect effect on snow leopard predation behaviour. Animals, such as markhor and ibex, must also move seasonally in response to the shifting distribution of alpine vegetation while snow leopards adapt their hunting ranges to prey abundance (Forrest et al. 2012). Community-based conservation in protected areas has contributed to localized population increases of snow leopard prey species. However, the decline of wild prey like the markhor (*Capra falconeri*) and ibex (*Capra ibex*) continues due to illegal hunting and habitat fragmentation and loss (Michel et al. 2015; Yasmeen et al. 2022) and competition with livestock for forage (Rosser, Tareen, and Leader-Williams 2012), leading snow leopards to resort to preying on livestock (Suryawanshi et al. 2017). This indicates behavioural plasticity, but such shifts may escalate human-wildlife conflict, especially in the Trans-Himalayan pastoralist areas. Changes of this nature in dietary composition highlight the versatility of the species but also increase the chances of retaliatory killing by the local communities. Snow leopards are subject to targeted killing attempts, further jeopardizing their already vulnerable population (Shrestha et al. 2022). Moreover, this shift is altering the snow leopard's hunting patterns and territory use. Instead of roaming high-altitude ridgelines and remote cliffs, they are increasingly active near human settlements, making livestock more vulnerable to predation. These changes could also disrupt natural prey-predator dynamics and lead to a cascading effect on alpine ecosystem structure. Over time, repeated targeting of livestock may even result in learned behaviours being passed down to cubs, making conflict mitigation more challenging.

2.4. Enhanced Interactions Between Humans and Snow Leopards

Under warmer scenarios, snow leopard and prey habitat are predicted to decrease and shift upslope causing a shift in space-use patterns to areas farther away from human-settled zones (Zhou et al. 2025). In the last few decades, however, remote camera traps have documented increasing detections of populations of snow leopards near villages (Alexander et al. 2016). These encounters suggest more severe losses of habitat and prey. Closer proximity also makes livestock predation more likely, increasing tensions between local people and conservation efforts. In addition, contacts with snow leopards might lead to an alteration in behaviour and a reduction in their natural avoidance of humans, which is detrimental to their survival (Hansen and Aanes 2015). Heightened risks from this new spatial overlap include both livestock predation and direct threats to snow leopards themselves, such as dog

attacks, snares, and retaliatory killing by herders (Wang et al. 2024).

Snow leopards are reported to approach livestock corrals and even enter them during the night, especially in areas adjacent to villages during times of prey depletion and increasing human land use (Zaman, Jackson, and Hussain 2024). These increasingly frequent interactions suggest a gradual loss of their instinctive wariness of people, a behaviour that could lead to higher mortality rates and complicate coexistence strategies. The psychological impact on communities should not be underestimated since fear, resentment, or financial loss may erode the local support needed for conservation initiatives to succeed (Jackson and Wangchuk 2001).

2.5. Interspecific Competition and New Eco-Interactions

The shifting climate will likely also result in expansion between snow leopards and other carnivore species such as wolves and lynx (Aryal et al. 2016). This could lead to competition or displacement and shift their behavioural ecology. Evidence of this is sparse, but some regions are experiencing these shifts, based on preliminary data (Lovari et al. 2024). These overlaps might increase the competition for common prey species which could lead snow leopards to change their hunting strategies and territorial behaviours. In some cases, avoidance, both spatial and temporal, may serve as a way to lessen active confrontation with other predators (Kachel et al. 2023). Furthermore, the addition of new predators or competitors into the snow leopard's range may affect the entire ecosystem and structure of prey populations more profoundly. Wolves in particular pose a threat since they are pack hunters and can control prey resources and possibly displace snow leopards from important hunting areas (Aryal et al. 2014).

Climate-driven changes in alpine ecosystems are increasingly implicated in even minor changes to snow leopard activity timing (Xiao et al. 2025). However, climate change will significantly alter the timing and location of predator hunting through the advancement of snowmelt, the postponement of the onset of winter and variation in the foraging cycle of prey species (Aryal et al. 2016). Such climate-mediated shifts in the timing of predator activity may cascade through alpine food webs, impacting prey dynamics, changing herbivory pressure on vegetation, and even restructuring community interactions (Henden et al. 2017).

2.6. Health Risks and Scavenging Behaviour

Reduced numbers of wild prey and increased competition from other predators might lead to increased scavenging which could in turn increase exposure of snow leopards to disease vectors present in carrion from wild animal or livestock carcasses (Ostrowski and Gilbert 2016; Chetri, Odden, and Wegge 2017) Moreover, higher temperatures may accelerate the dispersal of parasites and emerging zoonotic diseases into high-altitude habitats (Kutz et al. 2005). This increased exposure could suppress the immune robustness of snow leopards, making them more vulnerable to epidemics (Alexander et al. 2016). This sort of crisis might ultimately impose additional survival pressures on already isolated and fragmented snow leopard populations.

In addition, diseases that were believed to be confined to lower elevations now can take a toll on high-elevation carnivores (Scasta 2015) . For a species already experiencing low genetic diversity in some isolated populations, such infections could be devastating (Alexander et al. 2016). Health screening and proactive veterinary efforts will be of growing importance for the maintenance of viable populations in the coming years. However, since direct veterinary interventions are seldom feasible in such a secretive species, animal health-related monitoring should focus on livestock, sentinel prey species, and non-invasive techniques like faecal parasite screening. Such approaches can offer a first line of surveillance for disease

threats to more genetically susceptible snow leopard populations (Chetri et al. 2019).

3. Policy Integration

Climate change is rapidly remaking the world's ecosystems and landscapes, and it is becoming ever more apparent that traditional practices of wildlife conservation will not suffice (Prober et al. 2019). Snow leopard range conservation exemplifies the necessity of preserving the environment in a way that is as flexible and fluid as the environment itself. These high-altitude predators are not just losing habitat; they are also changing how they act, how they roam and where they reside (Riordan et al. 2016). If conservation efforts are to keep pace, our policies need to evolve just as rapidly.

3.1. Dynamic Protected Areas

Protected areas have historically been the building blocks of conservation, but boundaries are often based on old ecological information (Li et al. 2020). Climate change is rendering those static boundaries irrelevant (Hanson 2018). Over much of their known range, suitable snow leopard habitat is increasingly limited and fragmented due to climate change and the expansion of human land-use, particularly from treeline encroachment and decreased prey availability (Forrest et al. 2012). The way these cats move and hunt often does not align with static protected area boundaries and this mismatch highlights the limitation of inflexible conservation zoning (Forrest et al. 2012). Ecological forecasting and adaptive zoning that permit snow leopard habitats to contract or shift in response to climate change should be embedded into conservation planning. Instead of establishing fixed territories, conservation areas should be malleable, as already acknowledged in the design of climate-friendly protected areas (Hole et al. 2009; Watson et al. 2016).

3.2. Corridor Connectivity

For species with vast ranges, such as snow leopards, fragmented landscapes are a death sentence (Valentová 2017). With prey moving and habitats changing through the seasons, leopards need safe corridors to be able to move with them (Ghoddousi et al. 2020). Corridors on a map are not just pathways; they are lifelines. The maintenance of corridors, particularly those that link wild places at different elevations and cross political borders, is a means of survival (Sultan et al. 2022). Conservation efforts should continue to prioritise the protection of ecological corridors supporting snow leopard movement and gene flow across boundaries (Riordan et al. 2016). Connectivity among mountain populations lowers the possibility of genetic erosion, thus providing greater potential for long-term resilience to shifting climates (Farrington and Li 2024).

3.3. Climate-Smart Livelihoods

When snow leopards kill livestock, the impact is more than economic; it generates fear, resentment, and even deadly retaliation (Farrington and Tsering 2019; Juan Li, Hang Yin, Dajun Wang et al. 2013). Since wild prey is becoming tougher to find, we are seeing more of these encounters (Lovari et al. 2024). We must change the story from conflict to coexistence. This begins by providing herders with tools that make their way of life more resilient — such as livestock insurance, predator-proof corrals, and climate-smart grazing practices (Ghoddousi et al. 2020). Ecotourism and community-managed handicraft programs are examples of alternative livelihood initiatives that have eased livestock pressure and reduced conflict with predators (Vannelli et al. 2019). Worldwide, models such as community-based ecotourism in Ladakh have encouraged positive perceptions of wildlife conservation, especially for snow leopards (Watts et al. 2019). Similarly, properly designed handicraft and income generation programs have been shown to reduce poaching and retaliatory killing of snow leopards in Mongolia (Mishra et al. 2003).

3.4. Behavioural Monitoring Integration

To manage snow leopards in a way that is effective, we need to improve understanding of not just their habitat, but also of their behaviour. This will require a shift away from merely analysing population numbers and habitat towards analysing behaviour. Following their movements through GPS collars, watching patterns of behaviour in camera traps, and tracking their responses to seasonal and climatic changes provides vital information (Buchholz, Stamn, and Neha 2021). This type of data informs us when they are stressed, where they may come into conflict with humans, and how they are adapting to a changing landscape (Caravaggi et al. 2017). Incorporating behavioural science into conservation has been recognized as a key approach to improving decision-making and management outcomes (Durant et al. 2019). Conservation strategies are more effective when they account for behavioural flexibility and ecological trade-offs (Berger-Tal et al. 2011), since behavioural studies provide practical insights into species' vulnerability that can inform conservation interventions (Caro 2007).

3.5. Community-Based Approaches

Conservation does not take place in a vacuum but in villages, fields, and on mountain trails. The humans who share snow leopard habitat are often the first to know when ecological changes occur. Their assistance, testimony and experiences are critical (Kothari, Camill, and Brown 2013). Activating communities as partners, not as receivers, is a crucial point. This includes developing local capacity to track wildlife, empowering communities to resolve conflicts, and respecting traditional ecological knowledge (Ruiz-Mallén and Corbera 2013). When people feel heard and supported, they are much more likely to support conservation. In ecosystems as expansive and complex as the Himalayas, that human support is critical. In Ladakh, participatory approaches have bolstered co-existence with snow leopards (Mishra et al. 2003) and in Kyrgyzstan, successful community engagement has been associated with better conservation outcomes (Young et al. 2024). For some systems as large and complicated as the Hindukush region, community-based strategies are absolutely necessary (Khwaja 2022). Indeed, community engagement and participatory conservation approaches have been widely recognized as essential in Himalayan and Central Asian contexts (Foggin 2018).

3.6. International Agreements and Global Coordination

The snow leopard's territory does not recognize international borders, and neither should our conservation work. International coordination on snow leopard conservation will be necessary across its range, from Mongolia to Pakistan. Initiatives like the Global Snow Leopard & Ecosystem Protection Program (GSLEP) provide a potential structure for this. However, space for further integration of climate modelling and anticipated habitat shifts could bolster the long-term utility of GSLEP efforts (Zakharenka et al. 2016). Such integration may include using predictive models, establishing data sharing among countries, and linking local conservation initiatives to global biodiversity and climate targets (Lacher, Boitani, and Fonseca 2012). International donors and environmental funds also need to understand that snow leopard conservation requires a two-track strategy: supporting biodiversity conservation in tandem with providing assistance to mountain peoples in adapting to a warming world (Carle, Leslie, and Williams 2024).

Conclusion

As top predators of the alpine ecosystem, snow leopards face constant threats from anthropogenic and climate induced stressors and exhibit behavioural adaptations (Zhang et al. 2025). This dynamic, ranging from geographic expansion to changes in hunting behaviour, demonstrates the importance of adaptive conservation approaches (Lone et al. 2015). Although the species

has survived in its changing environment because of some climate-adaptive behavioural plasticity, accelerating climate change rates could exceed its ability to evolve. These changes can not only have direct impacts on snow leopard survival but also can ripple through the stability of the greater alpine ecosystems that they help to regulate. Conservation strategies must evolve beyond mere static protected area models to become dynamic, climate-informed, and inclusive of the communities who live in these ecosystems (Stralberg, Carroll, and Nielsen 2020). Ongoing conflicts based on local inter-species interactions can be addressed through climate and behavioural monitoring to provide early-warning indicators of ecological stress, while coexistence frameworks can be strengthened to mitigate rising human–wildlife conflict. Future research should prioritize long-term behavioural surveys and predictive modelling to better prepare for changing eco-dynamics.

Statements

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