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ORIGINAL RESEARCH

The decline of the Arabian Leopard *Panthera pardus nimr* in Saudi Arabia: a values-based plan for future management

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Abstract

The Critically Endangered Arabian Leopard (*Panthera pardus nimr*) has declined to near extinction in Saudi Arabia over the last fifteen or so years. In this paper we provide a time-series assessment of changes in the rate of leopard records since the 1930's and provide a values-based plan for the management of the species in Saudi Arabia. The number of leopard records rose sharply in the 1960's, peaking in the early 2000s, a time where human population growth and expansion across Saudi Arabia was also increasing. However, by 2014, the number of leopard records decreased to zero where it has remained. Based upon a clear need for effective conservation of the species, we developed a values-based management plan. In applying the planning framework, we defined the management system and its elements in their current state and the required state by the year 2050. From this work, a value-based goal was established, and four key management activities were recognised (and are expanded upon in the main text). We recommend that work is done to: (1) Ensure sufficient and suitable (in terms of required habitat and prey availability) areas are protected. (2) Reduce the level of human-based predation upon leopards to ensure sustainable mortality rates. (3) Manage the species metapopulation structure in terms of genetic makeup through natural and/or facilitated movement. (4) Continue to build community capacity and willingness to manage and protect the species. If these activities can be successfully completed, a population of Arabian Leopards can exist in Saudi Arabia if it is adaptively managed to deal with any additional and/or emerging threatening processes.

Keywords Values-based planning · Wildlife management · Species decline · Risk assessment · Management actions

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Introduction

What has happened to the Arabian Leopard (*Panthera pardus nimr*) in Saudi Arabia? The species was once widespread across the country (Judas et al. 2006), but by 2006, it was believed that the population had declined by around 90% (Fig. 1). Judas et al. (2006) utilized viability analyses to predict species extinction in Saudi Arabia by around 2010 and argued that increased levels of grazing (by goats, sheep, camels, and feral donkeys) and road building into remote areas impacted the surrounding food webs, reducing availability of prey species for the leopards. By reducing prey availability there will presumably be an increase in competition for food with other predators and an increased risk of people being attacked. It was then supposed that these changes meant that leopards were more likely to prey upon domestic animals, catalyzing unsustainable levels of human predation (Judas et al. 2006). Judas et al. (2006) recommended more surveying, increasing the area of land allocated to protect leopards, and the development of in situ conservation programs.

Shortly after the paper by Judas et al. (2006), Al-Johany (2007) reported on the distribution of the Arabian Leopard in Saudi Arabia, confirming the species still persisted in reasonable numbers in the Hijaz and Sarawat Mountains. Al-Johany (2007) felt that an important factor for the persistence of leopards in the Hijaz and Sarawat Mountains was continued prey availability and argued for a public awareness campaign and the creation of suitable protected areas. It should also be noted that Arabian Leopards have been bred in captivity (Boug et al. 2009). Between 1999 and 2018, 61 Arabian Leopards were held in breeding

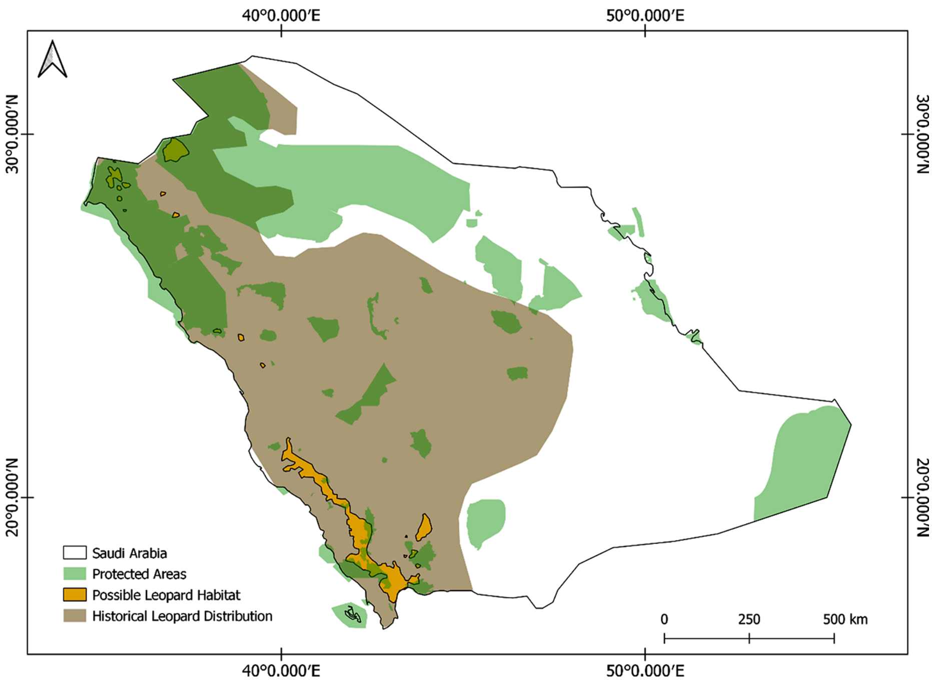

Fig. 1 Historical distribution of the Arabian Leopard in Saudi Arabia, location of Protected Areas, and proposed areas of suitable leopard habitat from Dunford et al. (2022). The state of the Arabian Leopard by 2050, in terms of its distribution and area of occupancy, will incorporate as much of the 'suitable habitat' as is practicable

centres across the Middle East (ZIMS 2018), indicating considerable potential to re-establish extirpated populations and to supplement any existing populations (Islam and Boug 2017). Further, releasing collared leopards provides great prospects to better understand the processes that drive leopard demographics in an area, thus providing additional opportunities to identify and ameliorate issues through sensible management.

Fast forward to the 2020's and the situation is dire. Islam et al. (2020) reported a population size of leopards in Saudi Arabia of around 50 individuals and used viability modelling to highlight the potential significance of competition for food and habitat destruction (in addition to human hunting) as drivers of leopard extinction. By 2023, it was thought there were fewer than 20 individuals remaining in the country (Islam et al. 2021; Islam 2022, Hadi Hikamani Pers. Comm. 2023).

Bearing in mind the decline of Arabian Leopards to actual or near extinction in Saudi Arabia, we:

(1) Provide a simple analysis of leopard records to further support the notion that the species is on the brink of extinction in Saudi Arabia, and
(2) Apply a values-based planning approach (Wallace 2012) to the management of the Arabian Leopard in Saudi Arabia.

Following the values-based planning approach, we:

(1) Identify key system elements,
(2) Set time frames and management boundaries,
(3) Suggest a preliminary values-driven management goal,
(4) Conduct a desktop direct risk factor analysis. Direct risk factors (Smith et al. 2015) are those factors that immediately impact upon one or more of the key rates of a viable population: mortality (or survival), birth (or fecundity), immigration, and emigration not.
(5) Identify and conceptualise key processes for management, and
(6) Develop a set of management priorities.

Methods

Leopard population status

To better quantify leopard declines, leopard records have been collected through personal communications and field surveys, in addition to the primary and secondary literature. In terms of personal communications, around 100 people were interviewed during leopard surveys conducted from 2008 to 2011 by M Z Islam and A Boug. The interviews included questions such as:

(1) When was the leopard last seen?
(2) Was the leopard alive or dead?
(3) Are there any photographs?

The interviews were carried out in areas where the leopard had been previously recorded and as such, local people provided historical information on the leopard in their area. More detailed descriptions of the data collection approach are provided elsewhere (Islam et al. 2018). The record information was analyzed in a simple but fit-for-purpose Bayesian time-series model of the number of leopards recorded each year from 1930 to 2022. Time series modelling can be complicated, but our question and data is simple and as such, we used an intercept only linear regression (Holmes et al. 2021). The model was run in JAGS (Plummer 2003) via the R2jags package (Su and Yajima 2021) deployed within the R software environment (R Core Team 2013). Code for the model was taken directly from Holmes et al. (2021, p. 350). Model formulation was:

$Y_t \sim Pois\left(\lambda_t\right)$, noting that our use of count data requires a discrete probability distribution such as the Poisson distribution. Additionally:

$E\left[Y_t\right] = \left[\lambda_t\right]$ and $log\lambda_t = x_t$.

x_t is a realization of X_t, a sequence of random variables. Prior parameters were set to:

u~dnorm(0, 0.01); # mean of the observation error.

inv.q~dgamma(0.001,0.001); # Inverse gamma distribution for residual error.

q <- 1/inv.q; # derived estimate for residual error.

X0~dnorm(0, 0.001) # mean of the observation error at time zero.

Standard Bayesian model checking procedures were applied (e.g., assessment of parameter convergence and autocorrelation) and a Bayesian-p value was generated to assess goodness-of-fit (Kéry and Schaub 2012).

Values-based planning framework

Information captured within the primary and secondary literature, in addition to expert information from key Saudi Wildlife Managers working for the National Center for Wildlife (https://www.ncw.gov.sa/en/Pages/default.aspx; last checked 02-02-2023) was used to apply the values-based planning approach. The planning framework has been developed by several authors (Wallace 2007, 2012; Pourabdollah et al. 2014, 2015; Smith et al. 2015, 2016, 2020; Wallace et al. 2016, 2020a, b, 2022; Wallace and Jago 2017, Smith and Wagner in Preparation). The basic premise of the approach is that the penultimate reason for managing wildlife is to maintain or improve the extent to which they are valued by people (Fig. 2). Importantly, there is a connection between how people value natural assets and their wellbeing, which constitutes the ultimate reason for managing natural systems (Wallace et al. 2020a). The approach has a series of steps that include defining key elements and their state (both at the initiation of management and for what is expected at the end of the management period), defining management boundaries and time frames, and developing a general values-based goal for management (Wallace 2012). A risk assessment is then conducted (in our case, a desktop review of the literature completed by the authors) and followed by the development of conceptual models and appraisal of management options (Smith et al. 2015). A final step is to develop a monitoring program (Wallace 2012), but we will forgo this step as it is addressed elsewhere (e.g., Jackson et al. 2006; Perez et al. 2006). We work through each broad step which is characterized in Fig. 2. We assessed and proposed a values-based goal for management, but we stress that ultimately the goal should be developed by the appropriate stakeholders or their representatives (Wallace et al. 2016) — a key recommendation from this work.

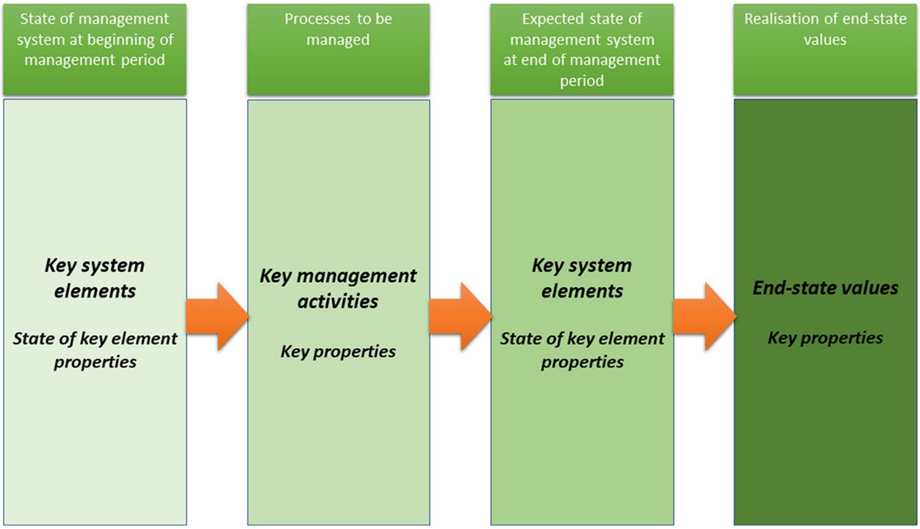

Fig. 2 Basis of the planning framework used here. Figure adapted from Wallace and Jago (2017)

Results

Leopard population status

The Bayesian timeseries model performed well (insignificant autocorrelation and no evidence of poor convergence) with a Bayesian-p value of 0.32 indicating a good model fit. Visual confirmation of a good model fit can be seen in Fig. 3 as the model estimates clearly fit the data extremely well.

The results of this analysis indicate that the leopard records increased during the 1960's and peaked by around 2000, after which there was a steep decline in records with the last occurring in 2014 (Fig. 3). Since 2014, there have been no new records of Arabian Leopards in Saudi Arabia. These results are consistent with previous estimates (Islam et al. 2021; Islam 2022) which inferred that the population of leopards in Saudi Arabia is very small (i.e., < around 20 individuals).

Planning framework

Step 1: Current state of the management system.

Summarised in Fig. 4, the key system elements of interested at the beginning of the management period and the properties relevant to management are provided in detail in Table 1. Key elements include the Arabian Leopard, people, leopard prey, and leopard competitors (Table 1). We also include elements associated with the habitat required by leopards, including water (Table 1).

A management period of 27 years from now (2050) was assigned, and the initial management area is bounded by the area defined by Dunford et al. (2022) as suitable habitat for the species (refer to Fig. 1). Over time, the management area will be redefined as new information becomes available.

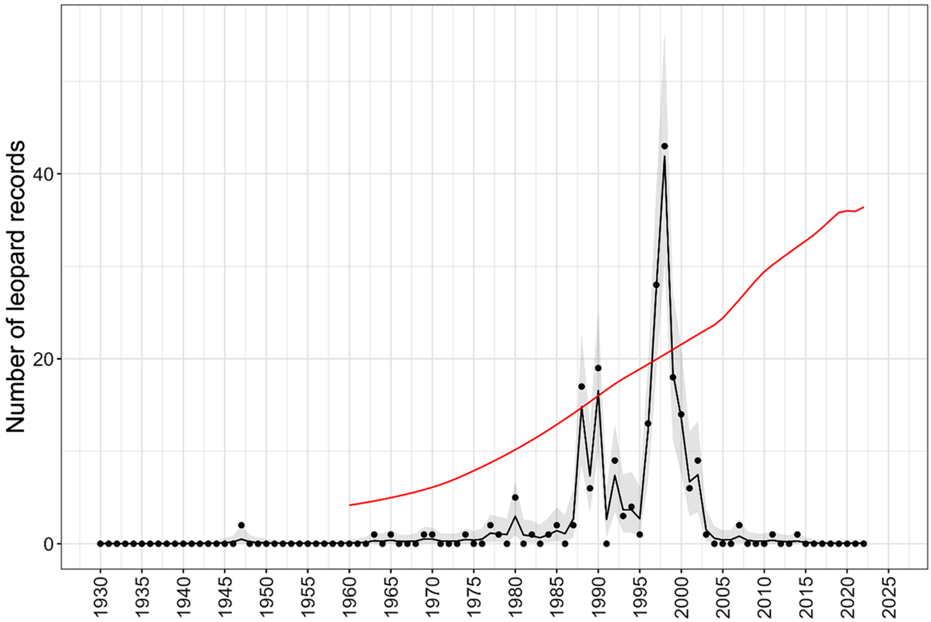

Fig. 3 Annual count of Arabian Leopard records in Saudi Arabia (black circle) and associated timeseries mean estimate (solid black line) and 95% Credibility Intervals (grey envelope). Red line shows estimate of human population in Saudi Arabia since 1960 (data provided by the world bank; https://datacatalog.worldbank.org/search/dataset/0037712; last checked 18/01/2023). Population reported as 'millions of people'

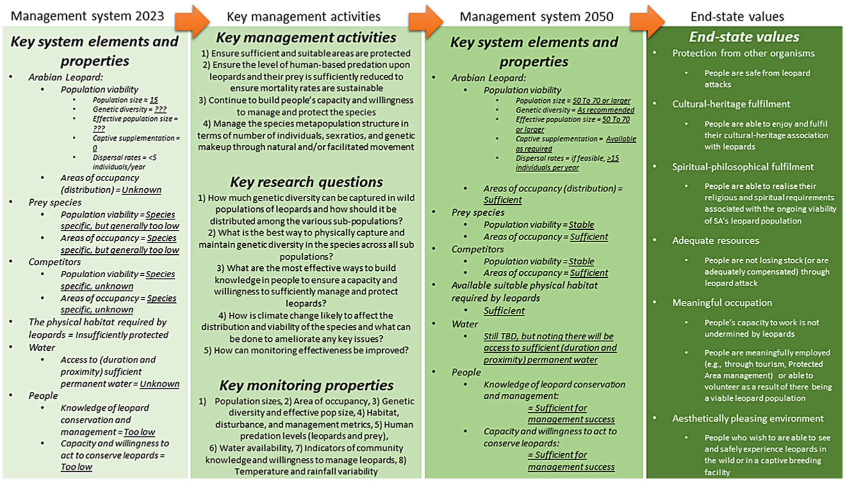

Fig. 4 Planning summary for the Arabian Leopard in Saudi Arabia

Table 1 System state at the beginning of the management period and the expected state at the end of the management period

State at beginning of management period			
Element	**Property**	**Sub-property**	**Estimate**
Arabian Leopard	Population viability	Population size	< 15
		Genetic diversity	Unknown
		Effective population size	Unknown
		Level of captive supplementation	0
		Successful dispersal rate	< 5
	Areas of occupancy (distribution)		Unknown
Prey species	Population viability		Species specific, but generally too low
	Areas of occupancy		Species specific, but generally too low
Competitors	Population viability		Species specific, but generally too low
	Areas of occupancy		Species specific, but generally too low
The physical habitat (excluding water) required by leopards	Access to sufficient denning sites		Unknow
	Access to sufficient resting sites/cover		Unknow
Water	Access to (duration and proximity) sufficient permanent water		Unknow
People	Knowledge of leopard conservation and management		Too low
	Capacity and willingness to act to conserve leopards		Too low
State at end of management period (2050)			
Element	**Property**	**Sub-property**	**Estimate**
Arabian Leopard	Population viability	Population size	50 to 70 (or larger)
		Genetic diversity	As recommended
		Effective population size	50 to 70 (or larger)
		Level of captive supplementation	Occurring as required
		Successful dispersal rate	If feasible, ≥ 15 individuals/year
	Areas of occupancy (distribution)		Sufficient to maintain population viability
Prey species	Population viability		Stable in areas occupied by leopards

Table 1 (continued)

	State at end of management period (2050)		
Element	**Property**	**Sub-property**	**Estimate**
	Areas of occupancy		Sufficient to maintain population viability
Competitors	Population viability		Stable in areas occupied by leopards
	Areas of occupancy		Sufficient to maintain population viability
The physical habitat (excluding water) required by leopards	Access to sufficient denning and resting sites, and cover in general		Sufficient to maintain population viability
Water	Access to (duration and proximity) sufficient permanent water		Enough (TBD) permanent water bodies per individual home range
People	Knowledge of leopard conservation and management		Sufficient for management success (TBD)
	Capacity and willingness to act to conserve leopards		Sufficient for management success (TBD)

Step 2: Expected state of the system at the end of the management period.

As described in Table 1 and summarised in Fig. 4, by the end of the prescribed management period, it is expected that there will be a population of between 50 and 70 leopards in Saudi Arabia that are existing in sufficiently protected and suitable habitats (with regards to freedom from hunting, and the availability of shelter, denning sites, water, and food). A managed metapopulation structure (e.g., local population sizes and genetic makeup) with an appropriate sex ratio will be achieved through open dispersal among protected areas inhabited by the species and/or by population supplementation with captive bred or wild caught individuals (Islam et al. 2020; Islam 2022). Ultimately, the population should have a suitably high effective population size (the size of which still needs to be determined) and have captured all the recommended genetic diversity. However, this may take more than one management period.

Step 3: Values-based goal.

Based upon the work of Wallace (2012); Wallace et al. 2016, 2020b), we provide a set of end-state values that we think are likely to be the key reasons for managing the Arabian Leopard with a level of justification for our classification (Table 2; Fig. 4). We stress that this is a preliminary set, and it will be appropriate and warranted to elicit from stakeholders or their representatives the ultimate set of end-state values relevant to the management of the Arabian Leopard and for them to rate the importance of each value (e.g., Wallace et al. 2016). We capture this point in the set of conceptual models (Supplementary Material 1). Based upon the definitions and preliminary ranking of the end-state values in Table 2, a suggested but preliminary management goal is to:

> Ensure that the Arabian Leopard in Saudi Arabia continues to be valued for its contribution to:
>
> (1) Cultural-heritage and spiritual-philosophical fulfilment,
> (2) People's capacity to enjoy meaningful occupational and recreational opportunities, and
> (3) An aesthetically pleasing environment.
>
> With successful management, the leopard will not undermine the capacity of people to:
>
> (1) Fulfill their resource requirements, and
> (2) Enjoy an environment free from the risk of animal attack.

The goal is contextualized by a 27-year management time-frame and the spatial boundaries that capture viable habitat for the species (Dunford et al. 2022). If the goal can be met, then the managed population of Arabian Leopards in Saudi Arabia is expected to contribute positively to the wellbeing of people, locally, nationally, and internationally.

Step 4: Process management

Structured risk assessment: Based upon our review of the available information, we propose that there are at least seven key risk factors that directly affect the species' demographic rates: predation, lack of food, lack of water, lack of mates, inbreeding, lack of key life media (by which we mean cover in addition to any required resting and denning areas),

Table 2 A Preliminary list of end-state values (based upon Wallace et al. 2020a) for the Arabian Leopard with associated descriptions

End-state values	Description	Leopard related issues
Cultural-heritage fulfilment	It is important to maintain any cultural and heritage practices associated with the use of wildlife. Leopards are likely to have significant cultural-heritage importance for people.	• Many people want to enjoy and fulfil their cultural-heritage connections, and for some people, this may be reliant upon a viable population of leopards. • There are strong cultural-heritage values associated with traditional knowledge held by 'local' people. This knowledge could be harnessed to mitigate carnivore related human-wildlife conflicts possibly with a program designed to compensate shepherds or people dependent upon livestock (as per provision of adequate resources below).
Spiritual-philosophical fulfilment	(1) The sustainable use and conservation of wildlife is enshrined in Islamic law and its principles. (2) In general, many people also have a fundamental 'wildlife ethic' and strongly believe that animals have a basic right to exist. We should try to ensure that right is maintained.	For many people it is important to realise their religious and spiritual beliefs. For many, this may be dependent upon a viable population of leopards.
Adequate resources	Leopards can be used for a range of medicinal purposes and leopards can attack livestock.	People do not want to lose their stock through leopard attacks and if stock are killed or injured by leopards, they will want appropriate renumeration.
Protection from other organisms	This is an important end-state value for people. Arabian Leopard attacks can be fatal and as such, needs to be managed.	People do not want to be attacked by leopards but it is worth noting that leopard attacks are rare.
Meaningful occupation	Leopards provide a meaningful occupation for many people whether it is for paid employment or the various volunteer activities related to its protection and management (this can include tourism activities).	• People do not want their capacity to work to be undermined by leopards. Whether it is related to loss of stock or if they can make money by selling leopards or their parts. Although leopard hunting is illegal, it will be worthwhile to find ways to provide people with alternate occupations. • Many people can be meaningfully employed or find volunteering opportunities related to the presence of a viable leopard population. These occupations may result from activities related to a tourism industry or through the management of protected areas and any corridors that connect protected areas.
Aesthetically pleasing	Leopards are a visually pleasing animal and as such it is likely that many people will derive considerable aesthetic enjoyment from a sighting.	Leopards are a visually beautiful animal and as a result, many people could fulfill their wants for aesthetic enjoyment associated with seeing and safely experience leopards in the wild or in a captive breeding facility.
Recreational satisfaction	People enjoy hunting leopards purely for recreational enjoyment.	This is a key values issue that needs to be managed. Leopard hunting as a recreational pursuit is very likely to very important to many people but is a significant risk factor for the species. An important management issue will be finding ways to encourage people to find recreational enjoyment related to experiencing leopards that does not impact upon species viability.

and hyperthermia. Based upon the literature, predation and a lack of food are considered to be particularly important direct risk factors (Judas et al. 2006; Al-Johany 2007; Islam et al. 2015). Preliminary conceptual models have been developed for the direct risk factors (Supplementary Material 1) which also include points of interest in terms of proposed conservation actions for the leopards and points of focus for important research. We now consider the key processes likely to affect these risk factors and list management approaches to ameliorate these issues.

Predation

Process description

Leopards are shy animals that typically avoid direct interaction with humans. However, the key reasons why human-mediated predation is prevalent relates to how and why people value the Kingdom's natural systems (Table 2). These reasons include:

(1) Economic drivers associated with a *meaningful occupation*, such as trading for fur and medicines,
(2) Hunting leopards to prevent any threats to lives (*protection from other organisms*),
(3) Hunting leopards as a *recreational pursuit*,
(4) Protecting livestock (Islam et al. 2015, 2018). If leopards become deprived of food, they are likely to prey upon livestock, leading people to hunt them to protect their livelihoods and food sources (*adequate resources* and *meaningful occupation*), and
(5) Accidental poisoning by people deploying laced meat to control other unwanted species (*adequate resources* and *meaningful occupation*).

Predation is likely to directly impact upon mortality rates but may also affect immigration, emigration, and birth rates.

Management

There are several key management options to reduce predation to sustainable levels—noting the definition of what is a sustainable level will need to be determined over time through adaptive management. These possibilities include:

(1) Effectively implementing the new hunting laws which were introduced in 2021 (National Center for Wildlife 2021) to curtail the critical issue of hunting pressure on a range of species, including the Arabian Leopard and its prey. This program is hoped to reduce the threat of hunting, not only on any remaining or future leopard populations, but for a range of leopard prey species also targeted by hunters (resulting in *a lack of food*). As part of these changes, a strong fining system is now in place (National Center for Wildlife 2021) which should act as a strong deterrent to hunting.
(2) Encouraging 'protected grazing ranches' in areas where leopard and other large predators occur in significant numbers. This approach should be facilitated by government assistance to support the creation of protective livestock enclosures consisting of galvanized iron piping and wire mesh.

(3) Increasing the knowledge of relevant communities about the importance of leopard conservation and its benefits. The knowledge held by relevant communities needs to be sufficient to change the capacity and willingness of enough people to act to conserve leopards. Although this will involve ongoing, adaptive and effective community engagement, a key step will be to formally elicit the reasons why and extent to which people value the Arabian Leopard (e.g., Wallace et al. 2016). This is a key recommendation of this document.

Armed with a clearer understanding of why and how people value leopards, managers can begin to better develop programs to fully involve citizens in the management of the species. Such participation will require programs with clear and effective aims, targets, and governance structures. Programs can:

i. Help to further develop meaningful occupations and the sustainable use of local natural resources, including alignment with tourism opportunities. There is scope to appoint and train wildlife rangers and environmental police to enforce local and national regulations against wildlife hunting and other similar activities,
ii. Aim for more 'local' natural resource management opportunities and knowledge building, including technical training for activities such as wildlife monitoring and the sustainable use and manufacturing of natural resources and associated products, and
iii. Seek additional opportunities to improve the economic benefits for people associated with maintaining a sustainable population of leopards. This may further reduce the impetus to hunt leopards.

We suggest that the management of this risk factor is feasible and can be very effective if sufficient resources and training are assigned to enforcement and if the community is successfully engaged and motivated.

Lack of food

Process description

Expanding agriculture (including management of grazing species), urbanization, and possibly mining can result in the degradation and removal of vegetation and wholesale reconfiguration of locally affected landscapes. This degrades the utility of these areas for leopards and often results in an overly fragmentated habitat (Franklin et al. 2002). Because of the far-reaching effects of these changes for a range of species (including prey for leopards), a 'fragmented' and degraded landscape can lead to reduced availability of food for leopards. This combined with increasing competition with other predators (such as *Canis lupus arabs* and *Caracal caracal*), means a given area will not be able to support as many leopards as it may have in the past.

Human hunting of prey species is also likely to contribute significantly to a lack of food. People in Saudi Arabia are known to hunt for several different species (including those required for prey by leopards; Alatawi 2022). The motivations behind hunting leopards include cultural fulfilment, recreation, and as a source of income as part of a meaningful occupation. These issues directly relate to why people value the species and as such are captured in Table 2.

If not already having an effect, a changing climate may also impact the distribution and diversity of many species preyed upon by leopards. A lack of food is likely to directly impact upon mortality rates, but may also affect immigration, emigration, and birth rates. With changing immigration and emigration rates, a lack of mates and inbreeding (both also direct risk factors) may affect birth rates.

Management

(1) Currently, the protected areas only cover a small portion of potential leopard habitat (Fig. 1), which must also be sufficiently sized and appropriately managed to sustain adequate food resources for the species. Thus, a clear management recommendation is to establish suitably sized and located protected areas that are sufficiently free from prey hunting (by effectively implementing the new hunting laws) and habitat modification by people for mining, agricultural, and urbanization purposes. Keeping the protected areas free from significant human landscape modification will be reliant upon legislation, regulation, and enforcement.

Where possible, it may also be important to reconnect or un-fragment currently disjoint areas of viable leopard habitat to increase the area available for leopards and their prey. Reconnecting and rehabilitating areas may require appropriate restoration of habitat (including provision of water and cover) and control of human hunting. This has been proposed by Islam et al. (2021).

(2) An additional option is to physically manage prey availability in Protected Areas. This may be achieved through captive breeding and release, capturing, and releasing wild prey species, and/or supplementing areas with ‘prey’ carcases.

We recommend that the management of this risk factor should be assessed in terms of the feasibility and effectiveness of the different options. For example, it may not be feasible to protect, restore, and manage sufficient areas of leopard habitat to reach the management goal.

Lack of mates and inbreeding

Process description

As noted above, there are several issues relating to increasing fragmentation of habitat both within and among protected areas that appear to be reducing leopard densities and limiting dispersal. Another consequence of these issues is a decreasing capacity for leopards to find appropriate mates and increased likelihood of inbreeding. The last record of a dead Arabian Leopard was in February 2014 (Fig. 3), when a sub-adult male leopard was poisoned (Islam et al. 2018). Islam et al. (2018) hypothesized that the individual was dispersing to find a new mate and/or to establish its own territory. An additional possibility that was considered was dispersal to avoid competition for food (Islam et al. 2018). Natal dispersal has been reported for majority of leopard species when they reach sexual maturity (Balme et al. 2013), which presumably helps to avoid inbreeding and enhance levels of genetic differentiation and adaptation. Safe and effective dispersal of individuals should help to connect more isolated populations, lowering the risk of stochastic extinction (Fahrig and Merriam 1994).

Management

There are two key management responses to this issue. The first, as described in point (2) above, is to create enough protected areas to support the desired population size. The second is to manage metapopulation issues. A transboundary management program between Saudi Arabia, Oman and Yemen is likely to be a critical management option for the leopard. This program has been identified as important (Islam et al. 2018, 2021) because it will allow movement of leopards (whether natural or facilitated) among the sub-populations, providing gene flow. The program will require significant cooperation, but if successful, will enhance protected areas in all countries. Of note, the largest, least fragmented, but unprotected habitats for the leopard are in and around Oman (Spalton and Al Hikmani 2014). Protecting and linking other populations to this area, either physically or through assisted dispersal, will be critical to the successful management of the species.

It is important to note that many of the border areas are highly protected and fenced, and as a result, it is unlikely that leopards can easily disperse through at least some of these areas. As noted above, this issue is most likely to be ameliorated by human facilitated dispersal. Without sufficient habitat (including prey species, cover, resting and denning sites, and water) and the capacity for individuals to successfully disperse, the population size of leopards in Saudi Arabia will continue to decrease with associated genetic consequences (Wilcox and Murphy 1985; Saunders et al. 1991; Wiens 1995) as has been shown for other leopard subspecies (e.g., Uphyrkina et al. 2001).

A clear definition of what is desired in terms of the metapopulation structure for the species is still required and should be developed. We also recommend that the various management options for this risk factor require an assessment of feasibility and effectiveness. For example, it may be more effective and feasible to physically manage geneflow among sub populations through captive breeding/wild-wild translocation than trying to create movement corridors among different areas.

Captive-breeding can play a vital role in the conservation of the Arabian Leopard including the maintenance of a genetically diverse population. In Saudi Arabia, a captive-breeding program for the Arabian Leopard was initiated in early 2000 and continued until 2017. In 2018 the captive-breeding program was handed over to the Royal Commission for AlUla (RCU).

The captive-breeding of Arabian Leopards in Saudi Arabia has been addressed elsewhere (Islam et al. 2020). However, we do note here that captive breeding is an important management activity because:

(1) Where major risk factors have been addressed, captive released animals can survive well in the wild.
(2) It can help to maintain a genetically diverse population. Captive-breeding programs carefully manage the breeding of leopards to ensure that the captive population is as

genetically diverse as possible. This is important for the long-term health and viability of the species.

(3) It provides animals for wild supplementation and for reintroduction programs. Captive-bred leopards can be used to reintroduce the species to its former range.

Lack of water

Process description

Leopards usually get moisture from their prey and consequently, can go without water for long periods. Although leopards can survive without water for a long time, during drier periods and/or periods where prey are less available, leopards are likely to rely upon access to water—noting that in captivity at the Prince Saud Al-Faisal Wildlife Research Centre (https://www.ncw.gov.sa/en/aboutus/pages/researchcenters.aspx#collapseOne; last checked 12/02/2023), leopards have been observed drinking water. However, with a changing climate along with reduced prey availability, the removal of wetlands, and extraction of ground water (through agriculture, mining, and urbanization) it is likely that leopards will be forced to seek water more often. A lack of water may have several effects on population viability, including a reduction in immigration and increase in emigration rates as affected areas may not be able to support as high densities of leopards as they did in the past. These changes may lead to an increased mortality rate and impact upon birth rates through a lack of suitable mates, which may also cause inbreeding.

Management

This issue should be relatively easily and effectively managed if suitable water sources can be protected and where required, managed in terms of ensuring water is available to leopards and their prey during critical periods. Additional water points could be created as required, whether in protected areas or in dispersal corridors. Important water sources should be identified, mapped, and protected.

Hyperthermia

Process description

Leopards occur in intermediate elevations (Dunford et al. 2022). Species that prefer intermediate altitudes may be particularly susceptible to increasing temperatures if they are 'pushed up the mountain' to extinction—so to speak.

Management

At this stage, we suggest that there is considerable scope to research the potential effects and if required, solutions to hyperthermia for leopards in the future.

Discussion

The Arabian Leopard in Saudi Arabia is imperiled. Here, we provide additional information to confirm the state of the species in Saudi Arabia and provide a values-based plan of management to ameliorate key risk factors. In terms of our population analysis, the human population and the rate of leopard detections increased starkly from the 1960s (Fig. 2) up until the 2000's, after which the human population continued to grow while the leopard population appears to have declined rapidly. We infer that with increased human population size, there was more opportunity for people and leopards to interact, resulting in more observations. However, with the growing human population and changing land use, we suggest that the leopard population has declined, becoming increasingly inviable, leading to a sharp decrease in observations after 2000.

For planning purposes, key system elements were defined as was a spatially and temporally contextualized values-based management goal. The goal can be realized by changing the current state of the system elements to one that will allow people to value the Arabian Leopard in Saudi Arabia more fully. To achieve this, at a minimum, four priority management activities must be successful. We need to:

(1) Ensure sufficient and suitable areas are protected.

   a. Collectively, these areas will require adequate cover, food, and water to sustain a viable population and be free from significant and unsanctioned human habitat modification and hunting of leopard prey species.

(2) Ensure the level of human-based predation upon leopards is sufficiently reduced to ensure mortality rates are sustainable.

   a. This can be achieved through a mixture of enforcement and improvement in people's capacity and willingness to manage and protect the species.

(3) Continue to build people's capacity and willingness to manage and protect the species. This should begin with the appropriate organizations properly understanding why and how people value the leopard, which can only be fully achieved through stakeholder elicitation of some form. This information should be used to develop citizen-based management programs that ensure people can:

   a. enjoy meaningful occupations and recreational pursuits,
   b. obtain resources in a sustainable manner,
   c. fulfill their philosophical, spiritual, and cultural-heritage requirements,
   d. derive aesthetic pleasure, and.
   e. not live in fear of leopard attacks.

(4) As described earlier, define and then manage the species required metapopulation structure in terms of number of populations, individuals per population, sex ratios, genetic makeup, etc. Future planning periods may look to increase the size of the population(s) with a view to becoming less reliant on captive bred animals. This will need:

a. a defined level and distribution of regional genetic heterogeneity,
b. a target for local and overall effective population size, and
c. an assessment of the required contribution and effectiveness of natural and/or assisted dispersal. For example, creating ‘corridors’ for dispersal between protected areas may simply be unfeasible and ineffective and dispersal might be better achieved by a mixture of captive releases and physically moving wild-caught individuals.

These results indicate several priority areas for research, which include determining:

(1) How much genetic diversity can be captured in a wild population of leopards in Saudi Arabia and:

    a. is that enough to avoid serious genetic issues, and
    b. how should that diversity be distributed among the various sub-populations?

(2) Given point (1), what is the best way to physically capture and maintain genetic diversity in the species across all sub populations (i.e., create dispersal corridors or manage assisted dispersal)?
(3) What are the most effective ways to build knowledge in people to ensure a capacity and willingness to sufficiently manage and protect leopards?

    a. How can the number of leopards and their prey being hunted be adequately reduced?
    b. What are the best methods to ensure there is enough water and other required habitat elements for the species in protected areas?

(4) How will climate change affect the distribution and viability of the species and what can be done to ameliorate any key issues?

Conclusion

If the above-mentioned activities occur, we consider it likely that the Arabian Leopard will once again exist in the wilds of Saudi Arabia. But to achieve this, it will be critical that people are a major part of the solution, which requires the relevant authorities to continue to make efforts to fully understand why and how people value the species. If successful, and with ongoing adaptive management, where additional or new issues are identified and resolved, the Arabian Leopard in Saudi Arabia will continue to contribute to the wellbeing of people locally, nationally, and internationally.

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Declarations

Conflict of interest We declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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